COGNITIVE EFFECTS OF PHYSICAL MODELS IN ENGINEERING IDEA GENERATION

A Dissertation

by

VIMAL KUMAR CHERICKAL VISWANATHAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Approved by:

Chair of Committee,	Julie Linsey
Committee Members,	Daniel McAdams
	Richard Malak
	Steven Smith
Head of Department,	Jerald Caton

December 2012

Major Subject: Mechanical Engineering

ABSTRACT

Designers use various representations to externalize their ideas, physical models being an important one. Physical models are widely used by designers and their use is promoted as an effective design tool by industry and government agencies. However, very little is known about the cognitive effects of physical models in the design process; the available guidelines are conflicting. Some researchers argue for the frequent implementation of physical models, while others observe that the use of physical models fixates designers. In light of these conflicts, the research discussed in this dissertation focuses on understanding the cognitive effects of physical models and developing guidelines for aiding designers in their implementation.

A combination of controlled lab studies and qualitative studies is adopted to achieve said goal. The results from the controlled studies show that physical models supplement designers' erroneous mental models and help them to come up with more ideas satisfying the problem requirements. These studies also demonstrate that design fixation is not inherent in physical modeling, but it is caused by the Sunk Cost Effect. According to Sunk Cost Effect, as designers spend more time building physical models of their initial ideas, they tend to fixate more to the variations of those ideas. A qualitative study on industry-sponsored projects and development cases of award-winning products further supports these results in more realistic situations. Further, the studies reported in this dissertation show that physical models can be effective tools for the mitigation of fixation to undesirable design features in a flawed example; however, these results can also depend upon the experience level of a designer in solving open-ended design problems.

With these insights from the series of studies, a set of guidelines and a Model Error Reeducation Method (MERM) are formulated and tested with novice designers. MERM helps designers in identifying critical loads and interface designs they miss in their original designs, before prototyping. The results from the testing of this method show that this method is very useful in avoiding said errors in physical modeling.

ACKNOWLEDGEMENTS

I would like to express my greatest sense of gratitude to my committee chair, Dr. Linsey, for her guidance, encouragement and constant support throughout the course of this research. I would also like to thank my committee members, Dr. McAdams, Dr. Malak and Dr. Smith, for their support.

Significant amount of help has been provided by Dr. Aaron Taylor, Department of Psychology, Texas A&M University for the statistical analysis of many experiments in this thesis. I would like to acknowledge his help here.

I am grateful to all the students who participated in my studies. This would not have been possible without them. I would like to thank my lab mates in the Innovation, Design Reasoning, Engineering Education & Methods (IDREEM) Lab for their support and encouragement. I would also like to thank Texas A&M University and the Department of Mechanical Engineering for giving me an opportunity to be a part of it.

Thanks also to all my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

Finally, I would like to thank my parents and sister for their encouragement and love.

Partial support for this research is provided by the National Science Foundation CMMI-1000954. Any opinions, findings, and conclusions or recommendations expressed in this thesis are those of the author and do not necessarily reflect the views of the National Science Foundation.

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CHAPTER I

INTRODUCTION: ENHANCING DESIGNER CREATIVITY THROUGH PHYSICAL MODELS

We live in an ever-changing world where our needs, quality of life and aspirations are dynamically changing. In order to meet the increasing needs arising from the changing demands, the nurturing of creative, innovative engineers is a necessity. Innovation and creativity are described as the two essential qualities for the engineer of 2020 [1]. Until recent times, it has been believed that these skills are gained through experience and cannot be taught. However, recent research has provided strong support for the teaching of creativity and innovation. In order to nurture these skills, it is essential to gain deep understanding of these qualities. Innovation and creativity are highly complex processes including many factors like prior experiences, team dynamics, representation of ideas, motivation, etc. With a proper understanding and modification of these factors, creativity and innovation can be enhanced. On the basis of this argument, this thesis studies the effect of a powerful tool – the use of physical models as idea generation aids – in enhancing designer creativity.

Engineering design involves complex manipulation of designer's internal conceptual representations [2, 3]. These internal representations play a key role in inventive thinking. However, the capacity of these internal representations to deal with highly complex problems is very limited [3]. External representations, such as sketches, physical models and virtual models, share this load, helping to amplify the thought process [2-5]. This leads designers to utilize various external representations in their design process. Physical models are well-liked external representations that designers employ in their idea generation process.

Physical Models in Engineering Design

Physical models refer to prototypes, of any scale, built to mimic certain aspects of the final design [6, 7]. They range from very rough mock-ups to accurate, fully functional prototypes. For example, Figure 1 shows the various physical models built by the developers of OrangeX Manual Citrus Juicer, during its design. These models range from two-dimensional motion studies to fully functional wooden model. On the other hand, Figure 2 shows an example of highly complicated, but non-functional physical models built by NASA in the early phases of the design of the next lunar lander [8]. The famous product design firm IDEO strongly recommends the frequent use of physical models in the design process [9]. The giant automobile company Toyota uses physical models to identify the problems in their design before beginning the costly production process [10]. Despite their wide-spread implementation in the design process, the cognitive impacts of physical models remain largely unknown.

Figure 1: Various physical models used by the developers of OrangeX Manual Citrus Juicer during its design [11]

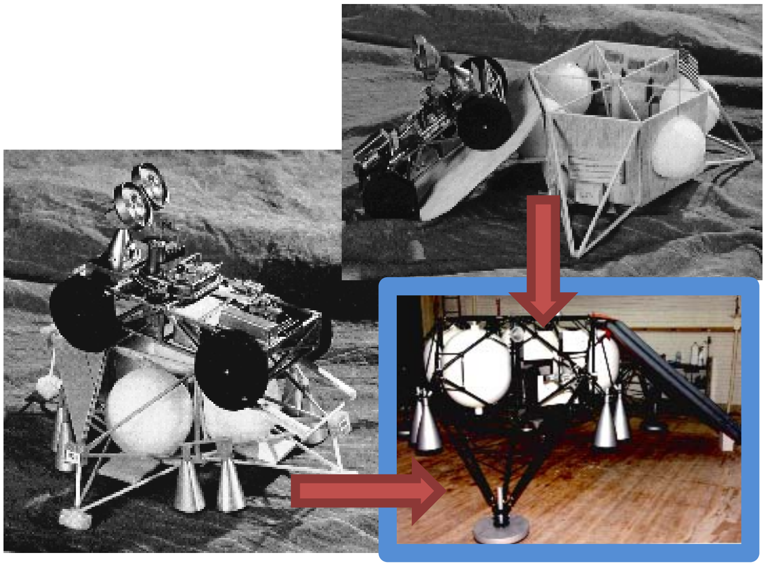

Figure 2: A set of Styrofoam and wood physical models built by NASA during the early phases of designing the next lunar lander [8]

Existing literature provides very limited and conflicting insights regarding this issue. Experienced designers, based on their prior experience, decide which representation is suitable for their needs at a particular stage of the process. For students and novices, it is extremely hard to determine the desirable representation due to a lack of well-documented guidelines. Based upon these issues, this research focuses on the cognitive effects of physical models on novice designers.

Design Fixation in Engineering Design

The role of designers' prior experience in solving open-ended design problems can be a major factor affecting their idea generation. Similar to most of the studies on engineering idea generation available in literature, this thesis also uses engineering students as participants for most of the controlled experiments. This is mainly due to the easy accessibility of this population in an academic environment. However, it is intriguing to investigate how the insights from such studies can be mapped to the idea generation by experts. One of the studies described in this thesis compares the ideas generated by engineering design faculty with those by novice designers (students), to prove the generalizability of the insights presented in this thesis for a larger population of designers.

A major concern in engineering idea generation pertains to design fixation, which hinders the conception of novel ideas. Researchers have studied the effects of pictorial examples [12-14] and physical models [15, 16] on imparting fixation in engineering idea generation process. A prior study by Jansson and Smith [12] shows that both novices and experts are susceptible to fixation induced by presented examples. Purcell and Gero [14] repeat the same experiment with mechanical engineers and industrial designers, finding that mechanical engineers fixate on the presented examples whereas industrial designers do not. These findings indicate that educational biases may play a role in fixation. A few studies in Psychology and design have looked into the role of domain expertise on fixation. Wiley [17] shows that domain expertise in baseball may cause a high degree of fixation in solving problems that requires non-routine thinking such as a remote association task. Baseball experts use baseball related terms to complete the remote association task more frequently than non-experts. The study by Linsey et al. [13] shows that even researchers with experience in design and knowledge of design theory, also fixate upon an example solution. The last two studies described in this thesis investigate the effects of design experience and representation used to convey examples on design fixation.

Research Questions

The existing anecdotal and empirical evidence offers highly conflicting views and guidelines about the implementation of physical models. This necessitates further exploration of their role in design cognition. The overall research question investigated in this thesis is stated below:

Can physical Models help designers in their idea generation process?

This question is further divided into the following testable hypotheses which are studied through various controlled and qualitative studies:

Physical models supplement designers’ erroneous mental models and lead them to higher quality solutions to design problems.

Design fixation is not inherent with physical models. The fixation observed in prior studies about physical models is due to the Sunk Cost Effect.

Physical models aid designers in mitigation of fixation to undesirable features in examples and their ideas.

When designers use physical models as idea generation tools, they tend to fixate to the variations of their initial ideas. At the same time, designers also tend to fixate to the examples they encounter in their everyday activities in the form of pictures or physical objects. This experimental paradigm effectively set what their first idea is. It can be either a variation of the examples they have already encountered or a brand new idea which fixates them in the generation of further ideas. However, designers may mitigate this fixation as they gain more experience in solving these problems. The second set of experiments in this research focus on the role of design experience and type of representations used to present the examples on design fixation. These studies can supplement the findings from the experiments on physical models and help to make those results more generalized. The questions investigated in these studies are the following:

Designers with more experience in solving open-ended design problems outperform novices in terms of quantity of ideas and they fixate less compared to novices.

The type representation used to convey examples does not affect the extent of design fixation to that example.

This research investigates these questions through a series of controlled and qualitative studies. The final goal of these studies is to develop clear guidelines for designers regarding the implementation of physical models as design tools. The problems that novice designers face while building physical models need to be understood. This research also targets to understand some cognitive aspects of design fixation and ways to mitigate that. As a part of the dissertation research, five controlled experiments and two qualitative studies are completed. The subsequent chapters in this thesis present the details of those experiments along with the description of results and insights obtained.

CHAPTER II

LITERATURE REVIEW

Engineering design involves a variety of activities beginning with the identification of a design problem and ending with the production of a finalized design solution. Of the various activities, idea generation plays an especially vital role in determining the quality of the final design [18]. Developing breakthrough products requires the generation of innovative concepts. Designers rely on an assortment of representations such as texts, sketches, computer aided models and physical models, to externalize their conceptualized ideas. Especially in dealing with complicated problems, external representations maintain a role of great importance due to designers' limited internal representation capacity [2, 3]. This thesis investigates the role of these external representations on engineering idea generation with a focus on physical models. This chapter presents a summary of the existing literature concerning the uses of physical models. In order to facilitate this discussion, the basic concepts from various fields of science and engineering are also presented and described. These concepts include mental models, memory, design fixation, sunk cost and learning from examples.

Mental Models and Memory

One aspect of mental models theory deals with people's perception of the physical world around them [19]. These mental models are often surprisingly erroneous [19] for both novices and experts [20, 21]. Kempton [21] shows that people possess erroneous mental models regarding the operation of their home heat control thermostat. Many think it operates like a car's accelerator, believing that the higher the setting, the higher the rate of heating. In realty, the rate of heating is constant; the thermostat controls the magnitude of constant heating, not the rate. Even in cases of highly trained professionals, mental models often contain errors [20]. Badke-Schaub et al. give another example of erroneous mental models pilots possess concerning the cabin altitude alarm leading to a plane crash [22]. When the cabin altitude alarm sounds, both the pilots think it as a take-off configuration warning, which occurs only at ground level. This example confirms the potential catastrophic consequences of erroneous mental models.

Studies in the area of mental models have important implications in engineering design. A designer's erroneous mental model may lead to infeasible ideas or ideas that do not satisfy all the problem requirements. Sketches, as the simplest medium for mental model expression [23], often reflect the errors in mental models. Consequently, idea generation using sketching as the medium of representation may lead to relatively low percentages of solutions satisfying all problem requirements.

As designers encounter a physical object, mechanism or sketch, they form a mental model of that and store in their memory [22]. As they observe new systems, they add that to their knowledge repository, ultimately forming a larger knowledge base [23]. Upon encountering a new design problem, a designer retrieves this set of mental models from memory and searches for any potential solutions within the existing knowledge repository [23]. From a design perspective, when designers suitably combine their existing knowledge about various components, they produce a solution to the problem.

When designers face a new open-ended design problem, they check in their memory for any feasible solutions. So, this mental repository is the basis for their initial solution space. Jannson and Smith [12] state that designers require prior knowledge to come up with solutions for new design problems, which is also in agreement with this argument. Thus, the limited knowledge stored in their memory may be a major constraining factor causing design fixation. By this argument, a person with a large repository of knowledge may fixate less compared to one with a small amount of information in their repository.

Design Fixation

Design fixation acts as a major obstacle to effective engineering idea generation. Jansson and Smith describe design fixation as, "the blind, sometimes counterproductive, adherence to a limited set of ideas in the design process" [12]. Similarly, in this thesis, design fixation is defined as *adherence to a limited set of ideas in the design process*. This adherence to a limited set of solutions leads to a reduction in the novelty and variety of ideas. Many studies in psychology demonstrate that idea generation is constrained by presented examples and initial ideas. Previous works show that introduction of pictorial examples of existing solutions to the problem restricts the designer's ability to produce novel solutions [14, 24-26]. The psychology literature explains this phenomenon using network models of memory [27-29]. In the network model, each node represents a concept. As examples activate the concept at a node, the probability of activation is higher for the nodes which are directly linked to the first one. This eases the retrieval of concepts similar to the first one from the memory and hence designers stick to the ideas which are closely linked to their initial ones.

Previous studies have explored two different kinds of fixation. Maier [30] described a type of fixation called "functional fixedness," in which the user cannot perceive any non-typical use of a device. Another type of fixation, as explored by Luchins and Luchins [31], is called "mental set." Said fixation involves people who are familiar with one solution strategy becoming unable to think of any new strategy. Both types of fixation constrain the solution space in which designers look for their ideas, forcing them to generate ideas which are variations of their initial ideas. This leads to a lower novelty and variety of the generated ideas; thus, design fixation is detrimental in an inventive design task.

A great deal of research exists concerning the role external representations play in design fixation. Many studies show that sketched examples can cause fixation in engineering idea generation (e.g., [12-14, 25]). A study by Cardoso et al. [32-34] has demonstrated that richer pictorial stimuli in the form of photos can also cause design fixation. Some studies illustrate that the use of physical models during idea generation also causes design fixation. Kiriyama and Yamaoto observe that graduate design teams generating ideas using physical models constrain their ideas to variations of their initial concepts [15]. Christensen and Schunn, in their observational study on practicing designers, observe that designers generating ideas with physical models produce a lower number of distant domain analogies [35]. Youmans shows that designers building physical models of their ideas fixate less to examples compared to those who do not [16]. In light of these conflicting findings, an explanation of the role of physical models in causing design fixation remains essential.

Expertise in Design Fixation

As explained above, experts are expected to possess a larger knowledge base formed from their exposure to a variety of problems. As the knowledge base in the memory forms designers' initial solution space, experts have a larger solution space to search and are expected to be less fixated compared to novices. Suwa and Tversky [36] show that experts can derive more information from their long term memory than novices, while solving problems. Chase and Simon [37] show that chess experts derive information from their memory in the form of larger chunks, which helps them to identify known chess-board configurations faster than novices. At the same time, when they are asked to identify random chess-board configurations, they perform poorly compared to novices. When experts face a problem which requires non-routine thinking like a creative design task, their expertise in a specific field acts as a constraint [17]. Their knowledge repository is restricted to their domain of expertise and this can lead them to fixation. Results from the study by Jannson and Smith [12] are in agreement with this. They explain that, years of educational and professional experience may contribute to fixation. This argument is further supported by the results from Purcel and Gero [14]. They show that mechanical engineers with specific domain knowledge fixate while solving design problems; whereas industrial designers fixate less. Hecht and Proffitt [38] show that waiters and waitresses, experts in handling glasses of water without spilling, perform poorly when they are asked to draw the correct configuration of water level in a tilted container, as shown in Figure 3. The correct configuration is portrayed by B in Figure 3, whereas majority of the waiters and waitresses fail to understand the fact that the water level remains horizontal regardless of the configuration of the glass. They attribute this phenomenon to the fixation to a frame of reference the participants are familiar with, in which the water level is parallel to the bottom of the glass. When the problem requires a shift in the reference frame, they fail to do so, which leads to their poor performance. This also shows the errors in their mental models about the water levels. Wiley's experiment [17] shows that subjects who are experts in baseball, fixate to baseball related terms in a Remote Association Task. She states that novices are more flexible in using their knowledge than experts.

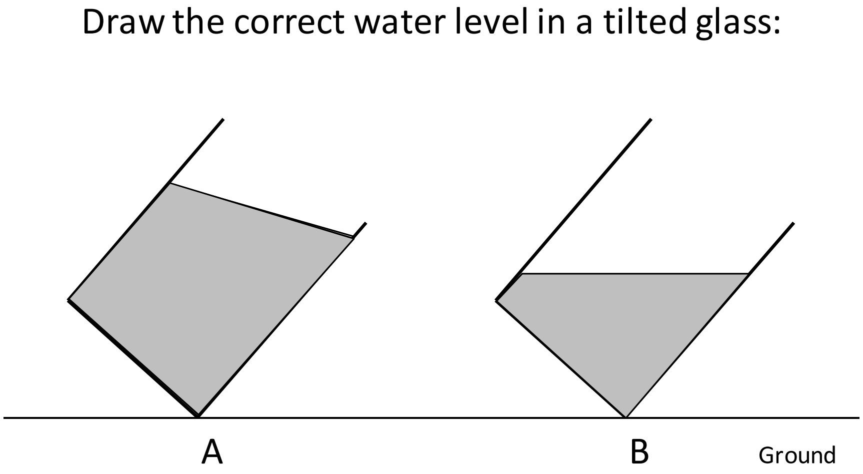

Figure 3: Solutions for the water level detection task provided to waiters and waitresses by Hecht and Proffitt [38, 39]. "A" represents the typical solution generated by most of the participants whereas "B" is the correct solution.

Another matter of concern is the educational or training process that allows experts to accumulate knowledge from a specific field or domain. Constrained design problems, often presented in engineering science courses, focus on a problem solving approach in which the students need to identify one core issue and devote their entire focus to that issue [40]. This type of an approach is not helpful in the early stages of engineering design when an innovative solution is desired, which requires diverse thinking and defocusing from the solutions already generated. Experimental evidence from Purcell and Gero [14] supports this argument. They show that industrial design students are far less fixated compared to mechanical engineering students. The practice of mechanical engineering students in their domain of expertise leads them to very limited variation in their ideas which are centred on their domain knowledge; whereas, the industrial designers may be trained to defocus their attention from specific domains.

Sunk Cost Effect in Engineering Idea Generation

Identified by behavioural economics, the Sunk Cost Effect manifests a greater tendency to continue in a selected path, after significant money, time or effort is invested in that path, even when an alternate path is more beneficial for the future endeavours [41-44]. Good decisions should be based on the expected costs of the choices in the future not past sunk costs [45, 46]. However, in actual practice, sunk costs do affect decisions, due to the Sunk Cost Effect [47]. Some good examples of this effect are portrayed by Thaler [48]. The resale prices of cars are generally guided by the current market price, whereas the sellers always decide based on the original buying price.

The Sunk Cost Effect can fixate designers to their initial ideas, especially when they spend more time or effect (costs) on those ideas. In engineering design, the cost can be money, time or effort that designers spend to solve a problem. Once significant investment of these resources is made into a particular solution path, designers tend to fixate to that path. In engineering design, the generation of highly novel ideas is important and this requires “out-of-the box” thinking. The adherence to one selected solution path can hinder this target. This can be especially true when designers build physical models of their ideas during idea generation. If this building process takes longer, the chances of fixation is also greater.

Learning from Design Examples- Analogical Reasoning

Researchers show that humans have the ability to extend their knowledge about one domain through its similarity with another domain by analogical reasoning[49, 50]. The use of examples in engineering education makes use of this ability. Examples help students learn new concepts by relating them to their day-to-day knowledge or to a more familiar domain. In analogical reasoning, the most challenging part is finding a suitable source analogies [51, 52]. If designers' local environment provides them enough hints to remind them of these solutions, it may largely help them in the idea generation process [53]. Examples present the students with these analogous domains, which makes analogical reasoning relatively straight forward[54]. However, Thagard [55] warns that good educators need to choose their examples wisely, so that they can be close to students' day-to-day experiences while being structurally and semantically close to the target. The presence of unwanted surface features in an example can lead students to fixate to those features[56], which can adversely affect the outcomes. Hence educators need to be careful in selection of their examples.

Physical Models in Idea Generation

A plethora of research demonstrates the importance of physical models in engineering design. Physical models help designers visualize concepts, estimate implicit attributes of designs, validate assumptions, verify functionality of ideas, enhance communication between disparate design teams and selection of the best concept [7, 57-64]. Sometimes physical models possess no functionality and are primarily useful for visualizing concepts. Conversely, completely functional models may help designers rectify problems in their designs before production [65]. Models often function as vehicles for mutual cognition and help capture information in the design, which are not otherwise available to designers [66]. Ward et al. [10] observe that the use of physical models at Toyota assists in the visualization of flaws in their designs, preventing the production of defective parts. Student design teams use physical models for identification of problems and unexpected behaviour of their ideas [62, 67, 68]. Smith and Leong [69] show that professional designers use physical models to learn about the design environment and value the use of physical modeling more than design students. Bucciarelli demonstrates that building physical models aids in the identification of energy losses in the design of a photovoltaic desalination plant [70]. These losses, not identified in the earlier stages of design, play a crucial role in the efficiency of the plant. In a similar way Faithfull et al. [71] describe building physical models as a means to increase the efficiency of control systems design and development.

Due to the importance of physical models in engineering design, many researchers encourage the use of such models. Tom Kelley of IDEO recommends the frequent use of physical models in product development [72]. McKim also encourages the building of physical models during early stages of the design process [4]. He testifies that building physical models helps encourage the visualization of problems in complex systems, leading to their solution. Also, he argues that externalizing ideas using sketching or building helps designers develop and explore them further. Physical models also minimize the risks associated with the initial assumptions of a design process regarding market acceptability, user features and the functions of the product [73]. They provide necessary information to the designers, enabling them to continue with their design, while minimizing cost [74]. Kiriyama and Yamamoto observe that graduate design teams use physical models to find the flaws in their design [15]. Acuna and Sosa has revealed that building physical models supplements the functionality of ideas [75]. Dow and Klemmer [76] demonstrate that designers who iterating on their ideas, with the help of physical models, can outperform those who do not iterate with physical models. A protocol study by Yang [77] reveals the benefits of limiting the quantity of details included in a physical model. She finds a negative correlation between the number of parts in physical prototypes and the quality of final designs.

In an effort to understand the cognitive effects of physical models, Youmans [16] studies students generating ideas for a device to collect objects inside a box, using only one hand, without touching the edges of the box. The students are asked to generate multiple ideas and present one functional idea at the end of the allotted time. He observes that students who build physical models of their ideas copy significantly less features from the given example, and their ideas are more likely to be functional. However, his study uses a complicated design problem, and the participants generate only a few ideas within the given time. In real-world idea generation, designers generate many solutions for a problem, build their physical models and select the best ones among them. To further explore the effects of physical models in idea generation, a design problem that designers can generate a large number of solutions for within the available time is studied in this thesis. This design problem also enables the study of the cognitive trends of idea generation with physical models over time. The variation of functionality of ideas with respect to the time at which they are generated is also investigated in this study.

Some prior work explores the role of physical models as boundary objects, i.e. objects shared across the boundaries of different problem solving contexts [78]. Engineering drawings are examples of boundary objects in new product development [79]. Repositories, data bases, digital images, story boards, Gantt charts and computer simulations are other examples [78, 80]. Boundary objects act as mediums for externalizing designer's ideas and communicating them to others. They also ease communication between groups of designers, especially when teams from various disciplines tackle different parts of the problem. Carlile suggests that physical models allow ideas in a designer's mind to be represented, learned and communicated in a group idea generation process and are thus good boundary objects [57]. They provide a concrete means to identify the differences and commonalities in the designs from various disciplines. By facilitating communication, visualization and understanding of concepts, they also act as an efficient means for research collaboration [81].

A few researchers have studied physical models as tools for training engineering students. Horton and Radcliffe [65, 67] observe that students who build physical models to obtain critical information in their class projects detect the flaws in their ideas and improve them. Youmans [16] shows that students who build the physical models of their ideas fixate less to the negative features of examples compared to those who sketch only. Some researchers encourage the use of physical models in engineering education as students can test their ideas and learn through their mistakes [82].

Some researchers provide warnings about physical models in the design process. Baxter cautions about the money and time involved in the building process [83]. Likewise, Buur and Andreasen argue for building models that possess an optimum set of properties for testing, since inclusion of unnecessary details leads to wastage of resources [84]. Vidal et al. find no advantage of idea generation with physical models [85]. An experiment with graduate design teams illustrates that physical models lead to a lower variety of solutions as designers tend to fixate to variations of their initial solutions [15]. Similarly, in their observational study, Christensen and Schunn show that physical models suppress distant-domain analogies in the design process [35], inhibiting a designer's ability to search various solution spaces. This also results in a lower novelty and variety of solutions. Kiriyama and Yamamoto also observe that physical models lead to design fixation in student design teams [15]. Considering these contradictory recommendations, a clarification of the role of physical models in design cognition necessitates itself.

Conclusions

The empirical evidence available from existing literature provides different and conflicting views about the implementation of physical models in engineering idea generation. This chapter presents a summary of previous efforts in literature concerning the use of physical models in engineering design along with the supporting concepts from the fields of engineering design, cognitive psychology and behavioural economics. The conflicting recommendations regarding the use of physical models make the implementation of such models as idea generation tools difficult. While experts can rely on their prior experience, novice designers may find the decision about the implementation of physical models, difficult. This thesis presents a set of studies investigating the role that physical models play in design cognition with the help of concepts derived from various disciplines. Based on the insights obtained from these studies, a set of guidelines and a design method for helping designers in the implementation of physical models are developed. The subsequent chapters provide details of the studies.

CHAPTER III

ROLE OF PHYSICAL MODELS IN DESIGN COGNITION – THE PAPERCLIP EXPERIMENT[1]

Despite the popularity of physical models in the engineering design process, their cognitive impact of remains largely unknown. As explained in Chapter II, the current anecdotal and empirical evidence offers highly conflicting views and guidelines concerning the implementation of physical models, necessitating further exploration of their role in design cognition. Experienced designers, based upon their prior experience, decide which representation is suitable for their need at a particular stage of the process. For students and novices, it is extremely hard to determine the desirable representation as well-documented guidelines are lacking. Based on these concerns, the study presented in this chapter focuses on the cognitive effects of physical models on novice designers.

Hypotheses

As explained in the literature review, the errors in designers' mental models can lead them to non-functional ideas. The study presented in this chapter explores whether the use of physical models can supplement these errors and lead them to more number of functional ideas. Consistent with the prior observational studies [15, 35], this study also

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[1] Part of the data reported in this chapter is reprinted with permission from "Physical Models and Design Thinking: A Study of Functionality, Novelty and Variety of Ideas," by Viswanathan V.K. and Linsey, J.S., ASME Transactions: Journal of Mechanical Design (Accepted for publication), Copyright 2012 by ASME.

hypothesizes that physical models cause design fixation. The two hypotheses investigated are stated below:

Mental Models Hypothesis: Physical models supplement designers' mental models, thereby leading to a higher fraction of functional ideas.

Fixation Hypothesis: Physical models cause design fixation, restricting the solution space, which leads to a net decrease in the novelty and variety of generated ideas.

These two hypotheses are investigated through a between-subject controlled experiment with engineering students. The subsequent sections of this chapter provide the details of the experiment along with an analysis and discussion of the results.

Method

The experiment reported herein was a between-subject experimental study conducted at Texas A&M University. This experiment evaluated the cognitive effects of physical modeling on idea generation. The utilized design problem was carefully chosen so that the participants could generate, within the given time, numerous fully functional prototypes from steel wire. In most cases, their prototypes were similar to the final product. The generation of numerous ideas by the participants enabled the study of the functionality trends of their models over time.

The participants were randomly assigned to four different conditions: Sketching Only, Building, Building & Testing and Constrained Sketching. In each condition, the participants spent most of their time generating ideas using the representation stated by the title of the condition. In the Building and Building & Testing conditions, participants were also allowed to sketch, but the conditions were called Building instead of Building & Sketching for simplicity. The Constrained Sketching Condition allowed any possible bias due to potential implicit constraints of the building materials and processes to be identified in the experiment. In this condition, participants received the building training prior to sketching their first idea. Across all the conditions, the experimental set up remained the same, but the representations used by the participants for the externalization of ideas differed.

The conditions evaluate the two hypotheses presented above. According to the Fixation Hypothesis, designers building physical models for idea generation fixate more compared to those who only sketch their ideas. If this happens, designers who build physical models will have a lower variety of ideas compared to those who sketch. As indicated by the Mental Models Hypothesis, if physical models supplement and improve the designer's mental models about the behavior of wire and its ability to clamp paper together, designers should yield a higher fraction of functional ideas that satisfy the problem requirements.

Design Problem

All the participants were instructed to generate ideas for a small object made of steel wire, less than nine inches in length, that could bind, without damage, ten sheets of papers together (a paperclip). The exact problem statement is shown in Figure 4. This design problem was inspired by Petroski's explanation of the evolution of paperclip designs [86]. The intentional simplicity of this design problem attempts to illicit all potential participant ideas within the allotted 3 hours. If participants run out of ideas within the given time, one might eliminate the bias arising from the difference in time required to build or sketch an idea. Physical models of the majority of ideas were expected to be two dimensional. This might avoid the bias due to the dimensionality difference between sketches and physical models. The participants were told that they could use the duration of the experiment to generate solutions and were asked to produce a maximum number of solutions. They were also encouraged to generate non-conventional and technically infeasible ideas, since these could lead to unique solutions.

Design Problem: Design a small object made of only steel wire of maximum 9” length to bind papers together.

Requirement: The object must securely bind 10 pages of paper together, without any damage to the paper.

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

Figure 4: Design problem statement provided to the participants

Participants

For this experiment, all participants were undergraduate and graduate students from the Mechanical Engineering Department of Texas A&M University. Seventy six senior undergraduate and four graduate students volunteered for the experiment and they were randomly distributed across the four different conditions with twenty participants per condition. The graduate students were evenly distributed across the conditions to avoid any bias in the data. All the undergraduate students were recruited from the senior design classes offered at Texas A&M University. These participants had very limited practical experience with fabrication processes outside the classroom. The experiments were conducted in the middle of the semester to make sure the participants gained enough exposure to the design process, especially conceptual design. The participants were offered extra credit in their class or payment as compensation. They were informed that those who generated superior ideas would receive additional extra credit or a bonus payment. In fact, at the end of the experiment, this bonus was given to all participants to ease logistics. The participants were instructed to not discuss any aspects of the experiment with their classmates to avoid bias. The average age of the participants was twenty two years, and there were five female participants. One to four participants were run at the same time, but were separated by dividers to ensure the uniqueness of each participant’s ideas.

Tools and Materials

The participants built their models from 9” long steel wire. To facilitate the building process, participants also received all necessary tools, including: chain nose pliers, round nose pliers, safety goggles and wire cutters (Figure 5). After the models were finished, they were instructed to work harden their models with an arbor press, stiffening the paperclips and preserving their shape. A recorded 10-minute video training was provided to the participants at the beginning of the Building Activity. This video demonstrated the use of various tools and the procedure to work with the provided materials. The training was projected on a wall in front of the participants and narrated by a native, English speaker. The recorded training attempted to mitigate any bias due to variations in the training instructions given by a manual trainer. The participants were requested to follow along with the training activities so that they could gain some practice using the tools and materials.

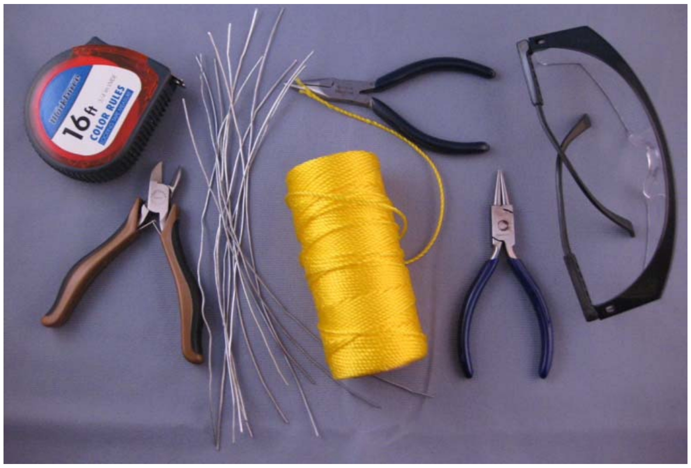


Figure 5: Tools and raw material used for building prototypes

Procedure

As the participants entered the experiment room, they were directed to their workspaces. These workspaces contained a table and a chair. They were separated from each other by dividers and curtains. In all conditions, participants were asked to sign a consent form. All the instructions for the experiment were pre-recorded with a native, English speaker. Various colors of pens were used to keep track of the time at which they generated a particular idea. Their pens were exchanged at five minutes and then every ten minutes thereafter. The time limit given for each activity is presented in Table 1. The participants were not informed of these time limits, but were told instead that they had as much time as desired. In actuality, they were required to use the entire allotted time for each activity, and were not allowed to move on. If they felt they had run out of ideas and desired to move on, they were instructed to think of more ideas and told that most people could come up with more solutions even after they thought they were out of ideas. All conditions ended with a survey.

It was advantageous if the participants finished building physical models of all of their ideas, because it could avoid the bias of another person building them. If the participants were unable to finish building during the experiment, they were asked to take the tools home, complete their designs and bring back the built prototypes for additional compensation. None of the participants, except one in the Constrained Sketching Condition, agreed to do this. Two individuals (the author and an undergraduate student), built and tested the paperclips which were not completed by the participants. The judges disagreed in only one instance, leading to a high inter-rater agreement (Cohen's Kappa of 0.97 and Pearson's correlation of 0.98), showing that the judgments of functionality of the designs by these judges were reliable.

The rest of procedure for each condition is described starting with the Sketching Only Condition below.

Table 1. Time Limits for various activities in the experiment

Condition	**Activity**	**Max time (Hrs: Min)**
Sketching Only	Idea generation with sketching only	1:45
	Building	0:30
	Testing	0:10
Building	Idea generation with building	2:20
	Testing	0:10
Building & Testing	Idea generation with building & testing	1:35
	Follow up sketching	0:35
	Building new ideas	0:10
	Testing new ideas	0:05
Constrained Sketching	Idea generation with sketching only	1:45
	Building	0:30
	Testing	0:10

Sketching Only Condition

Participants in this condition spent the majority of the three hours generating ideas using sketching. After consent, the participants immediately began idea generation on the given design problem. They were instructed to sketch one idea per pre-drawn box on the sheet of paper provided to them.

After the allotted idea generation time, they were provided with building training along with the tools and materials for prototyping. This training was intended to familiarize the participants with the tools and materials for building physical models. The participants were encouraged to repeat the activities on their own, along with the activities shown on the screen. Through this process, the participants were expected to reach the same level of fabricating ability with the provided tools and materials. After the completion of the Building Activity, they were allowed to test their ideas with ten pages of paper. The participants then marked the ideas satisfying the design problem requirements.

The last activity in this experiment was a Building Skill Measurement Activity. This activity attempted to estimate the relative sketching and building times of the participants to uncover any bias due to building skill variation. Participants were instructed to sketch the paperclips shown in Figure 6 as quickly and accurately as possible. Then they were asked to build the same paperclips as quickly and accurately as possible. For both tasks, their time of completion was measured. All the participants sketched and built the same paperclip, allowing the authors to compare their building and sketching times. The experiment ended with a survey.

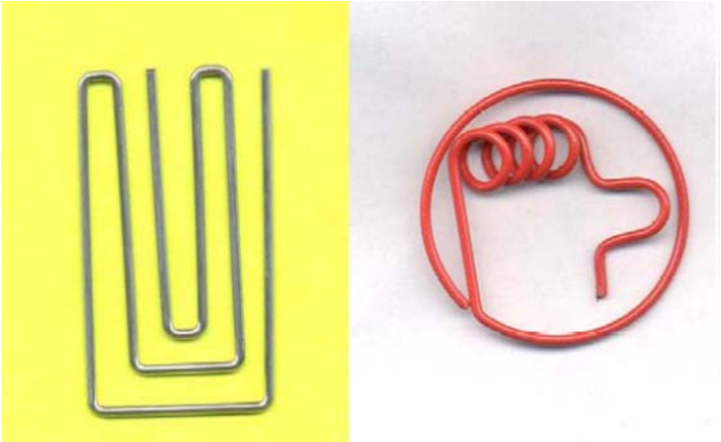


Figure 6: As a measure of sketching and building skill, participants sketched and built these paperclips during the Building Skill Measurement Activity

Building Condition

In this condition, the participants were allowed to sketch and build their ideas during the initial idea generation activity. Participants were instructed to sketch one idea and build it before proceeding to the next idea. The training to use the tools and materials was provided to them at the beginning of the experiment. All other activities remained the same as the Sketching Only condition.

Building & Testing Condition

In this condition, the participants were allowed to sketch, build and test their ideas during the initial idea generation activity. They were instructed to sketch an idea first, build it and test it before proceeding to the next idea. This was followed by a sketching only idea generation, referred to as Follow-up Sketching Activity. In the Follow-up Sketching Activity, the tools and raw materials were removed and the participants were asked to sketch more solutions to the same design problem. This was intended to test the learning effects (changes to the participants' mental models) due to physical modeling**.** By comparing the Testing while Building and the Follow-Up Sketching activities, the author was able to infer the physical models' learning effects. If designers learnt significantly from the Building Activity, then it was expected that they would generate the same percentage of functional ideas while sketching as they did while building. If the percentage was significantly different between the Testing while Building and Follow-Up Sketching, one might infer that the participants did not significantly learn from the model building. All other activities remained the same as in the Building condition.

Constrained Sketching Condition

This condition addressed any possible effects, to idea generation, from the implicit constraints associated with the building materials and process. If the use of physical models improved the percentage of functional ideas generated by the designers, it might be partially attributable to these constraints. This condition was designed as a variation of the Sketching Only condition. The major difference from the Sketching Only condition was that the participants were told that they would build the physical models of their sketched ideas after the Sketching Activity. To make them aware of the physical constraints imposed by the raw materials and tools, they were provided the training to use tools and materials at the beginning of the experiment. During idea generation, they sketched their ideas and later, built them.

Metrics for Evaluation

Three metrics, percentage of functional ideas, novelty and variety were used to evaluate the hypotheses [87, 88]. The first activity in each condition was designed to evaluate hypotheses and the subsequent activities, such as testing, marking the ideas satisfying the requirements and additional building, facilitated the evaluation.

Expert judgment rating scales are very common in a wide variety of subjects, including the social sciences, business and psychology, where more objective measures are not generally available [89]. Three expert rating scales are used in this study: percentage of functional ideas, novelty and variety. All these metrics are independent of each other. To assure the reliability of these evaluations, inter-rater agreements are measured. In this case, two independent judges are asked to measure the outcomes separately according to pre-set rules. An inter-rater reliability coefficient is calculated between the two ratings. This is a common approach for assuring the reliability of measures [24, 25].

Percentage of Functional Ideas

To evaluate the effects of physical models on designer's mental models, the number of functional ideas generated by each participant was counted. The participants were instructed to put each of their ideas in a separate box on a sheet of paper, making it very clear how many ideas they generated. A functional idea was defined as an idea that satisfied all the design problem requirements. The participants were asked to test the functionality of ideas and identify their functional ideas. One author also judged the functionality of each idea from built prototypes. Judging the functionality from a sketch was more difficult than from a built prototype. If a prototype successfully held ten sheets of paper without damaging them, and met all other design problem requirements, it was considered to be functional. The average Pearson's correlation between these two evaluations was 0.85, which was significant. These judgments were based upon the design's ability to hold ten sheets of papers together. This could be easily tested and judgments could be made with little ambiguity. The high inter-rater agreement between the participants' and the raters' judgments validated these two evaluations. In the end, only participant's judgments were used in this study because they involved no judgments or interpretation of the sketches by the experimenter, decreasing bias. Since the amount of time required to build ideas was greater than the time required to sketch, and the idea generation time allowed for all conditions was not sufficient to run out of ideas, the number of functional ideas was normalized to the total number of ideas. The percentage of functional ideas evaluated the Mental Models Hypothesis. If the physical models improved designers' mental models, a higher percentage of functional ideas, as compared to the Sketching Only Condition, are expected in the Building and Building & Testing Conditions.

The Follow-up Sketching Activity in the Building & Testing Condition measured changes in the designers' mental models (learning effects). Again the percentage of functional ideas was used. This fraction was compared between the ideas generated in the Follow-Up Sketching Activity to the Testing while Building Activity. If there was a learning effect due to physical modeling, the percentage of functional ideas should be approximately the same in the Follow-up Sketching Activity as in the Testing while Building Activity.

Novelty and Variety

For evaluating the fixation due to physical models, variations of the novelty and variety metrics were employed [88, 90]. If physical models induced design fixation, then lower novelty and variety was expected in the Building and Building & Testing conditions. Another measure of design fixation was the total number of ideas generated, but since more time was required for building and as the participants did not run out of their ideas, this metric could not be used for this study. If participants had possessed sufficient time to run out of ideas in every condition, then the total number of ideas could be used. One of the goals of using a simpler design problem was to allow participants to run out of ideas so that the results were more representative of what designers did as they search the entire idea space for ideas.

To efficiently measure novelty and variety, the prototypes were sorted by two independent judges who were blind to the conditions. The ideas sketched by the participants were more ambiguous, hence the models were used to calculate the novelty and variety scores. The judges sorted the built models to bins of similar ideas using their own criteria for sorting. The variety score of a participant was defined as the fraction of the total solution space that the participants' ideas occupied [88, 90]. Thus, it was computed as the ratio of the number of bins that the participants' ideas occupied to the total number of bins [91]. If a participant developed one novel solution and then generated numerous variations of it, the novelty metric was less reliable. In these experiments, no participant did this. An inter-rater agreement (Pearson's coefficients) of 0.79 for variety and 0.91 for novelty was obtained for the sorting, which was significant enough for a satisfactory inter-rater agreement [92]. This showed that the method employed was reliable.

The novelty score for each concept was the number of similar concepts divided by the total number of concepts. This was measured as one minus the frequency of ideas in a particular bin [12] (Equation 1).

$$\text{Novelty} \quad = 1 - Frequency = 1 - \frac{Number\ of\ ideas\ in\ a\ bin}{total\ number\ of\ ideas} \qquad (1)$$

In each condition, the participants first sketched their ideas. Any difference between the results from the Sketching Only Condition and the building conditions might come from the effects of building physical models. In real life situations, designers sketch their ideas before building physical models. Consequently, the combined effect of sketching and physical modeling is of interest. A comparison of the metrics across the conditions proved especially useful in addressing this issue.

In many cases, the participants sketched a few ideas that utilized electricity, magnetism and similar resources. These ideas were considered to be non-buildable and could not be accounted for by the sorting of built prototypes. In order to eliminate this bias, the idea sketches were sorted separately by the same two judges. The novelty and variety scores were calculated separately from these sorts as well. Inter-rater agreements (Pearson's correlations) of 0.67 for novelty and 0.63 for variety were obtained for these idea sketches. These low values could be attributed to the inherent ambiguity of the idea sketches. The functionalities of ideas were not clear from these sketches and the sorting involved the judgment by the reviewers about the functionality. The prototypes conveyed the functionality more clearly, which led the judges to sort them more consistently, resulting in high inter-rater agreement values. Hence, the novelty and variety values from the sorting of prototypes are reported as primary results here and those from the sorting of idea sketches are also included for the purpose of completeness.

Results

Hypothesis 1 - Mental Models: Percentage of Functional Ideas

Participants generated a large variety of paperclip designs. Many of them were non-functional revealing the possible errors in their mental models. For example, some participants generated ideas in which the small opening of a ring made of steel wire held papers together with the help of friction/elasticity. However, the stiffness of the wire was not enough for these clips to function. In this case, participants had wrong mental models about elasticity/stiffness of the provided steel wire. The percentage of functional ideas showed a difference across the conditions as shown in Figure 7. The variation of percentage of functional ideas across various conditions was significant, with a one-way ANOVA showing this statistically (Group: $F(3, 79) = 8.63$, $p<0.001$, $MS_{error} = 3.38$). These data satisfied the homogeneity of variance assumption, but were not normally distributed. The sample sizes were large enough, so ANOVA was robust to the violation of normality. To further verify this result, the analysis was repeated using a permutation test whose results matched with the ANOVA (Group: $F(3, 79) = 8.63$, $p<0.001$, $MS_{error} = 3.40$).

A-priori tests were chosen based on the theoretically interesting comparisons. These comparisons were determined based on the Mental Model Hypothesis. According to the Mental Model Hypothesis, building physical models could supplement designers' mental models and thus result in a higher percentage of functional ideas. To check this, percentage of functional ideas in Sketching Only Condition was compared against that in the Building and Building & Testing Conditions. The Building and Building & Testing conditions were compared for the same metric to infer any additional effect of testing physical models. The comparison of this metric between the Constrained Sketching Condition and the Sketching Only Condition enabled inferring any potential influence of implicit constraints on designers' mental models. Pair-wise a-priori t-tests [93] showed a significant difference between the Sketching Only and the building conditions (Building and Building & Testing conditions), as shown in Table 2. No significant difference in the percentage of functional ideas across the two building conditions existed. It was also observed that, although the Constrained Sketching condition showed some improvement in the percentage of functional ideas compared to the Sketching Only condition, the difference was not significant. The Constrained Sketching and Building conditions showed a difference in this metric, though it possessed no statistical significance. Still, the Constrained Sketching and Building & Testing conditions differed significantly in the percentage of functional ideas metric. This supported the argument that the building process affected the percentage of functional ideas. From this, one could attribute this result partially to the effect of the implicit constraints. In the end, the data illustrated that the difference in the percentage of functional ideas across the conditions arose from the combined effect of implicit constraints, from the building process, and the building process itself.

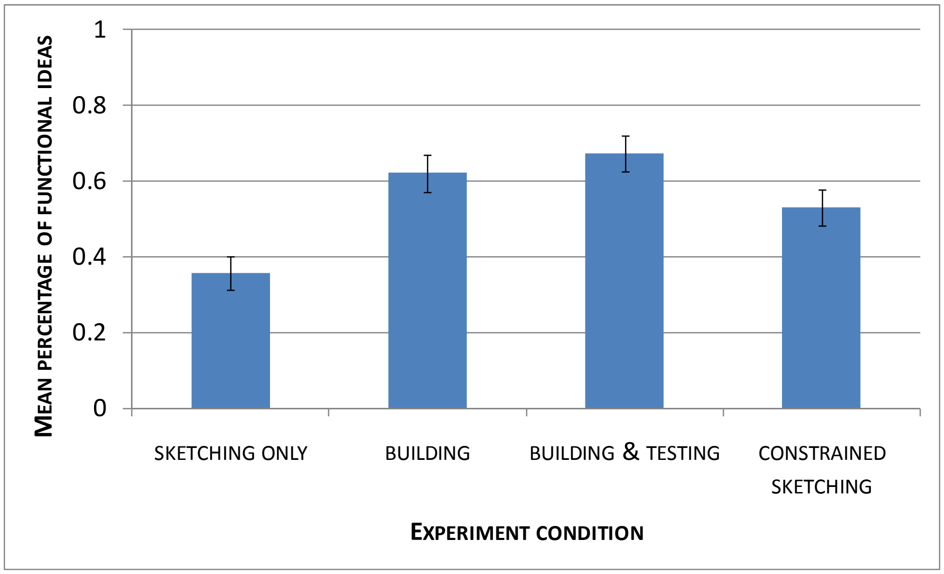


Figure 7: Mean percentage of functional ideas across the conditions (error bars are (±) one standard error of the mean).

Table 2: Results of a-priori t-tests for percentage of functional ideas for Experiment 2

Conditions Compared	t	P	Result
Sketching Only vs. Building	2.48	0.02	Significant*
Sketching Only vs. Building & Testing	3.22	0.01	Significant*
Sketching Only vs. Constrained Sketching	1.28	0.28	Not significant
Building vs. Building & Testing	0.25	0.80	Not significant
Building vs. Constrained Sketching	1.69	0.11	Not significant
Building & Testing Vs Constrained Sketching	2.38	0.03	Significant

* shows significant results for post-hoc tests with Tukey HSD correction

Figure 8 shows the mean number of ideas generated by the participants in each condition. Participants in the Building and the Building & Testing conditions generated less number of ideas compared to the Sketching Only and Constrained Sketching conditions. Since building physical models of ideas consumed significantly more time that sketching them, this result was expected. As a result, the number of functional ideas across the conditions would not be as good of a metric to compare the effect of physical models on designers' mental models. Therefore, the percentage of functional ideas was employed as a metric instead of total number of ideas generated.

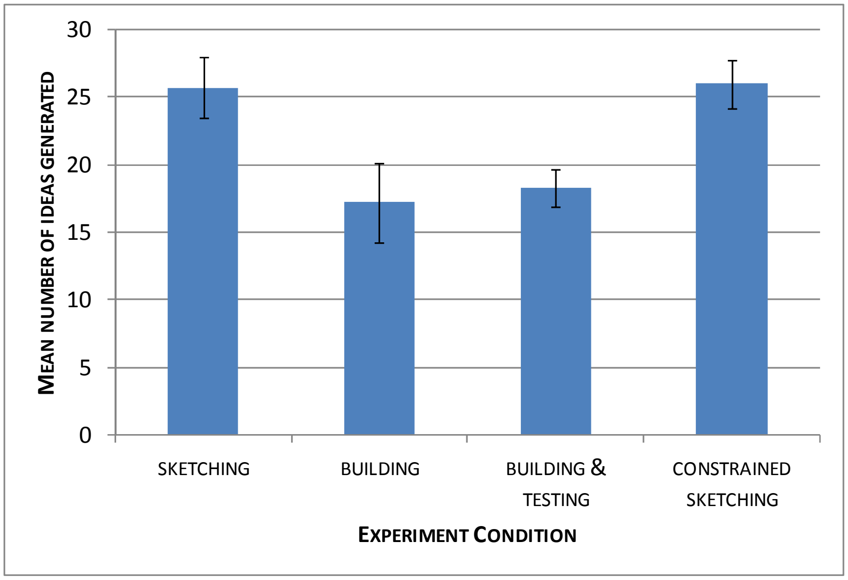


Figure 8: Mean number of ideas generated in each condition (error bars are (±) one standard error of the mean)

Potential Biasing Factors for Percentage of Functional Ideas

If the functionality of an idea varied with the time at which it was generated, the observed difference in the percentage of functional ideas across the conditions could be due, in part, to the fact that building requires more time than simply sketching. Said factor was one potential bias in the experiment. To investigate this, the percentage of functional ideas was plotted as a function of time (Figure 9) and as a function of the percentage of ideas generated by the participants (Figure 10). It was observed that the percentage of functional ideas decreased as a function of the time at which the participants generated the ideas. A logistic model showed that the interaction between time and condition in predicting the percentage of functional ideas was statistically insignificant ($\chi^2 = 4.95$, $p = 0.18$). This indicated that the percentage of functional ideas depended only on the experiment condition.

To investigate this issue further, the slopes of the regression lines in Figure 9 were calculated and a t-test was performed to determine if those were statistically different from zero (Sketching Only: slope = 0.07, t=0.80, p = 0.42; Building: slope = -0.26, t=-2.21, p=0.03; Building & Testing: slope = -0.06, t=-0.49, p=0.62; Constrained Sketching: slope =-0.15, t=-1.40, p=0.16). The results showed that the slope of the regression line for the building condition was significantly different from zero, indicating that participants generated more functional ideas at the beginning of the session. The bias due to this factor was 0.13%, not large enough to cause the difference in the results shown in Figure 7. Similarly, the regression line for the Constrained Sketching condition also deviated from zero, but the deviation was not statistically significant. Again, this would not cause the significant difference seen the in results shown in Figure 7. The participants had a slight tendency to generate more functional ideas at the beginning of the session than at the end, but this did not significantly impact the total percentage of functional ideas. Consequently, idea generation time did not bias the finding that physical representations assisted designers in generating more functional ideas.

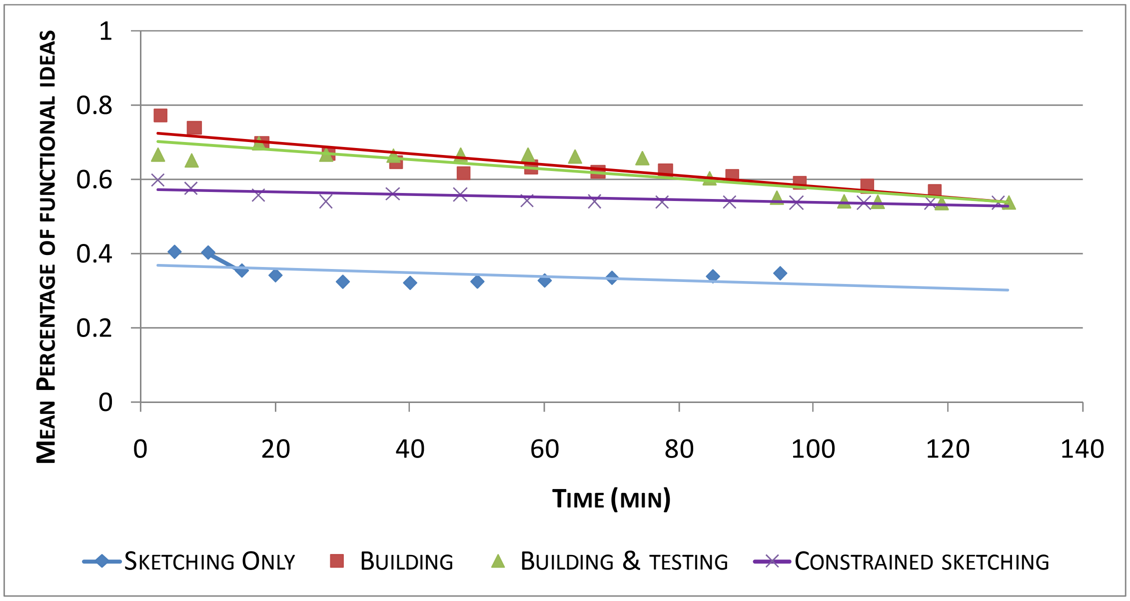


Figure 9: Mean percentage of functional ideas does not show any interaction effects between the time at which the participants generated ideas and the experimental conditions.

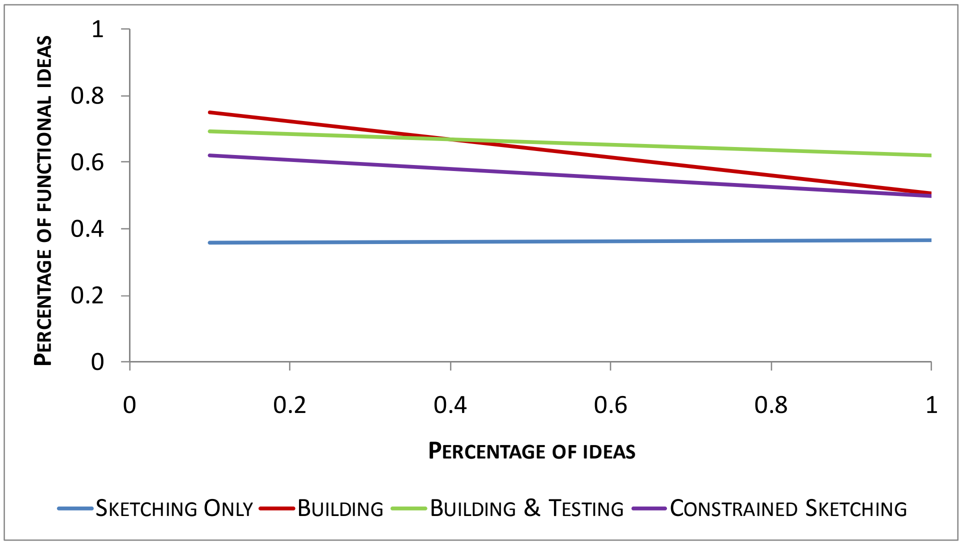


Figure 10: Mean percentage of functional ideas does not show any interaction effects between the percentage of idea generated by the participants and the experimental conditions.

Effects of Building Skills on Idea Generation

Another possible bias was the building skill of the participants. The time measurements from the Building Skill Measurement Activity were used to determine the participants' relative skills. This should not be considered an absolute measure for participants' building skills, but the comparison of the time they took to build a given paperclip design could act as a measure to identify any affect a participant's sketching and building skills had on their idea generation. The quality of sketched and built paperclips in this activity was rated by a judge on a scale of 1 to 5, where 1 was poor and 5 was excellent compared to the provided sketches. No correlation was observed between the quality of designs and the time taken to sketch and build them. The percentage of functional ideas, from the experiment, was plotted as a function of the sketching and building times (Figure 11 and Figure 12). The data for the first and second paperclips from the Building Skill Measurement Activity adhere to the same pattern. These plots show no significant variation in the percentage of functional ideas based upon participant sketching or building times. A linear regression was performed to confirm this (Sketching time: t (1,79) = 0.64, p = 0.52; Building time: t (1,79) = 0.72, p = 0.48). These results eliminated any possible bias in the results due to the difference in fabrication ability of participants.

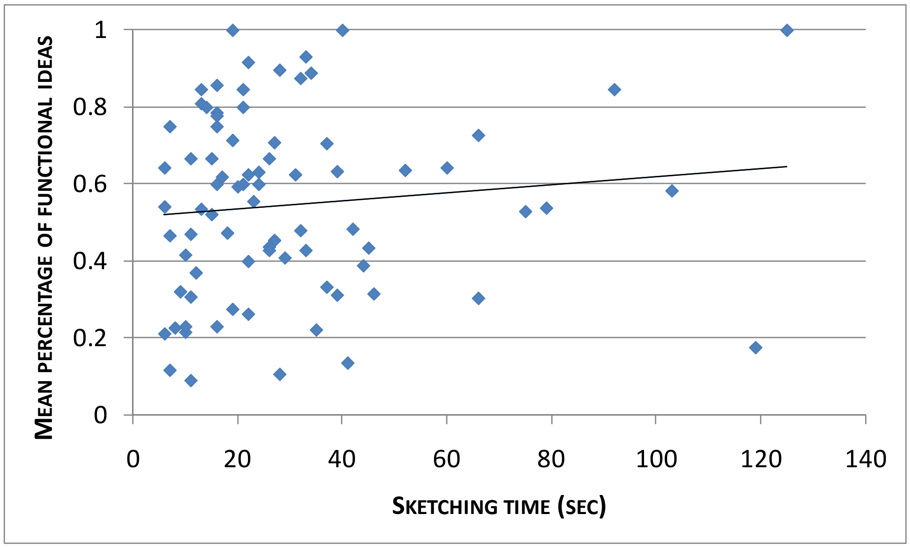


Figure 11: Percentage of functional ideas showed no significant correlation with participant's sketching time in the Building Skill Measurement Activity.

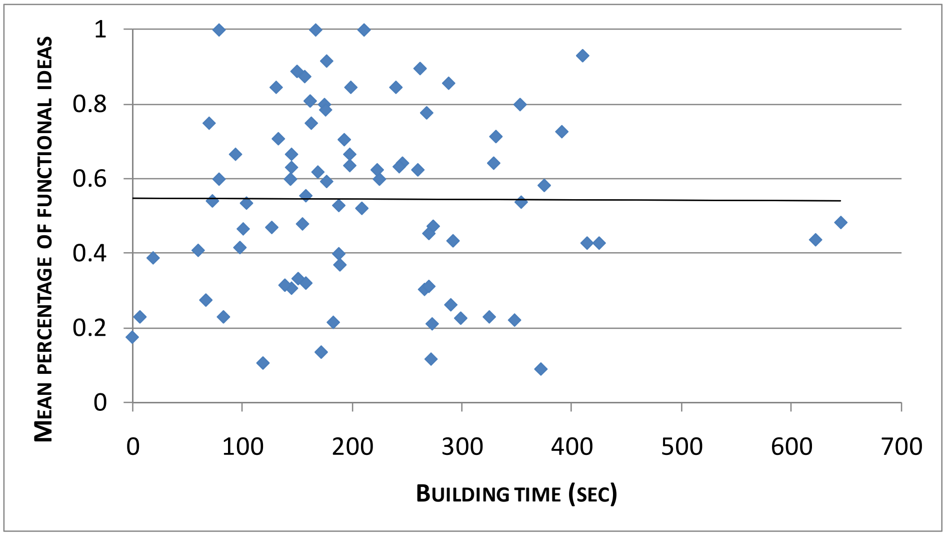


Figure 12: Percentage of functional ideas showed no correlation with participant's building time in the Building Skill Measurement Activity.

Hypothesis 2- Design Fixation: Novelty and Variety

Participants in general created many novel paperclips (examples in Figure 13). Majority of these paperclips were 2D clips, but there were a few 3D clips too as shown in Figure 13. Results showed no significant differences in mean novelty and variety across the conditions of this experiment (Figure 14 and Figure 15 respectively). A one-way ANOVA confirmed this (F(3,79) = 1.10, p = 0.35, MSerror = 0.01 for novelty and F(3,79) = 1.72, p = 0.17, MSerror = 0.01 for variety). Given that sketching the ideas and building them took a different amount of time, the total number of ideas generated in each condition varied. Since, in an actual design situation, a designer must only produce one very good design, the maximum novelty was also investigated. The ideas with maximum novelty, from each participant, were determined, and the mean of these values was taken in each condition. This maximum novelty remained the same across the conditions, as shown in Figure 16. A one-way ANOVA showed no significant difference of maximum novelty across the conditions (F(3,79) = 1.73, p = 0.17, MSerror = 0.13). These results seem to indicate that fixation was not occurring due to the building of models.

Figure 13: Sample paper clips that the participants made. These example designs include both functional and non-functional ideas.

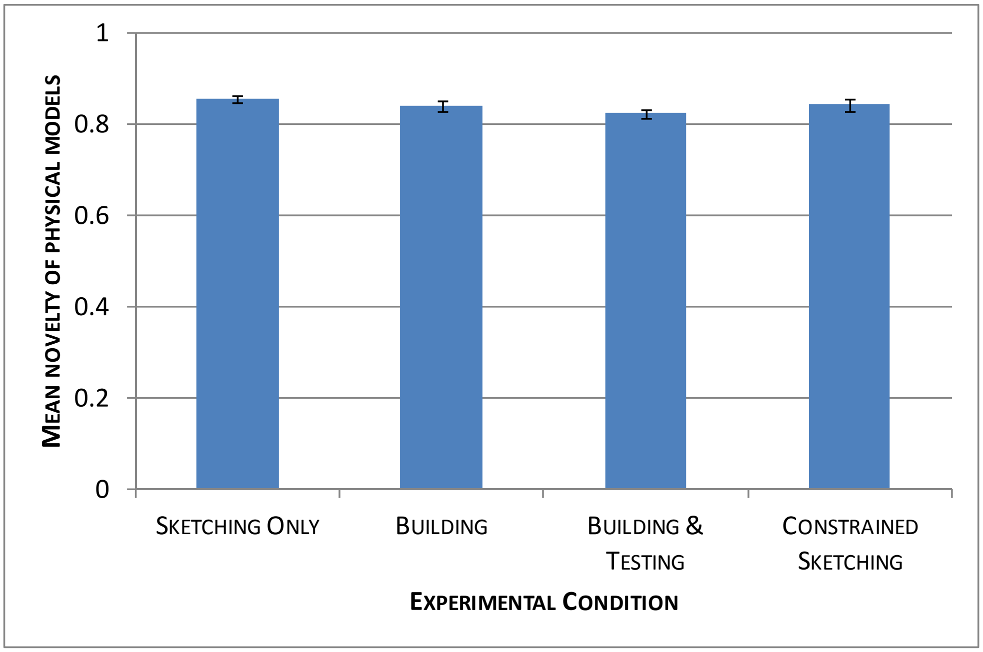


Figure 14: The mean novelty of ideas showed little difference across the experimental conditions (error bars are (±) one standard error of the mean).

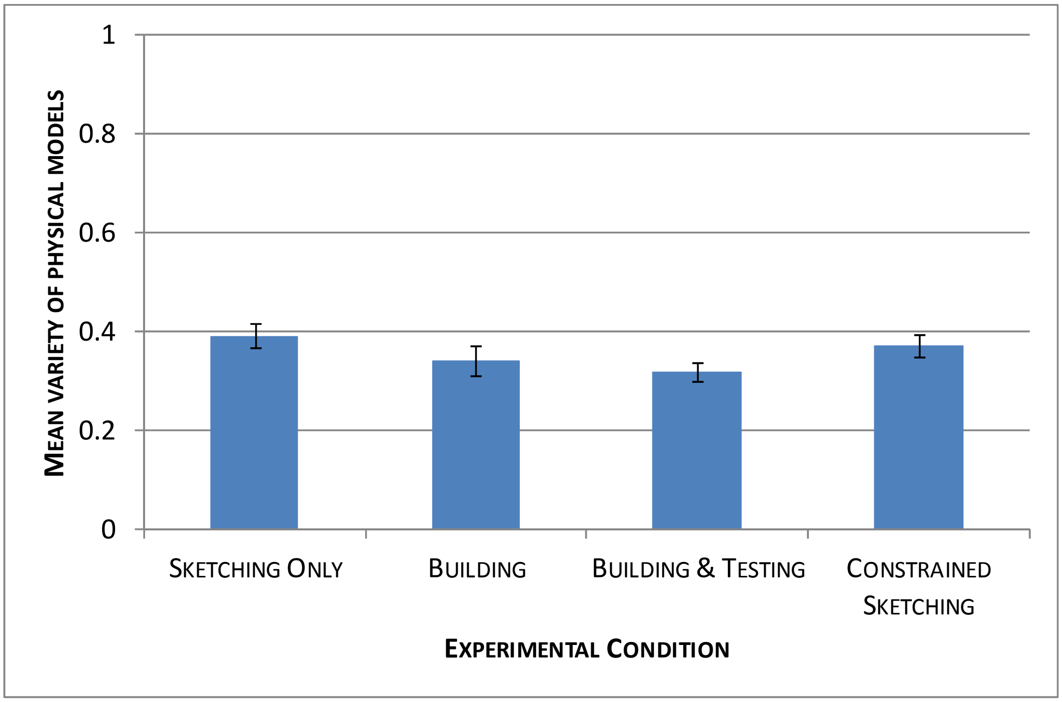


Figure 15: The mean variety of ideas did not show significant difference across the experimental conditions (error bars are (±) one standard error of the mean).

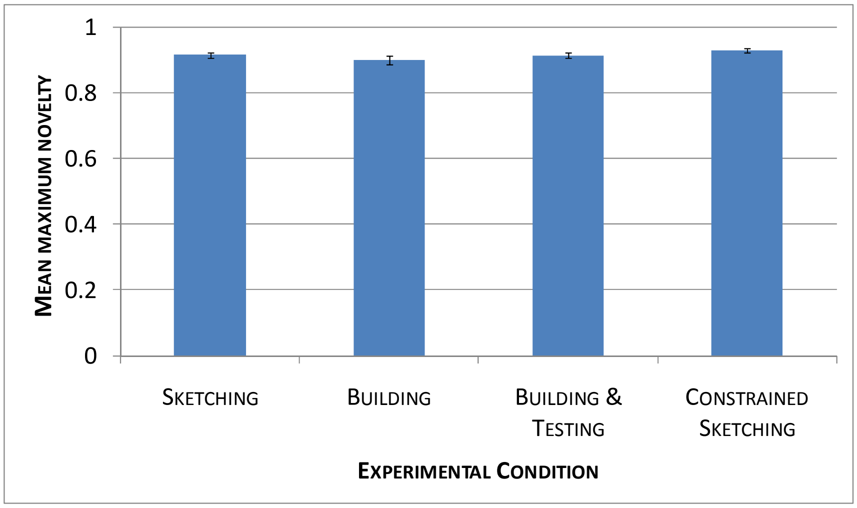


Figure 16: Mean maximum novelty per participant did not vary significantly across conditions. (Error bars are (±) one standard error of the mean).

As mentioned in the previous section, the results shown in Figure 14 and Figure 15 had a drawback. They only took into account the prototypes built, as they were obtained using sorting of the physical models. To rectify this, novelty and variety on the sketches showing the whole solution space created by the participants was analyzed. The results of this analysis are shown in Figure 17 and Figure 18. These results also showed no fixation across the conditions. In this case the inter-rater agreement was comparatively low, which might be due to the ambiguity of idea sketches.

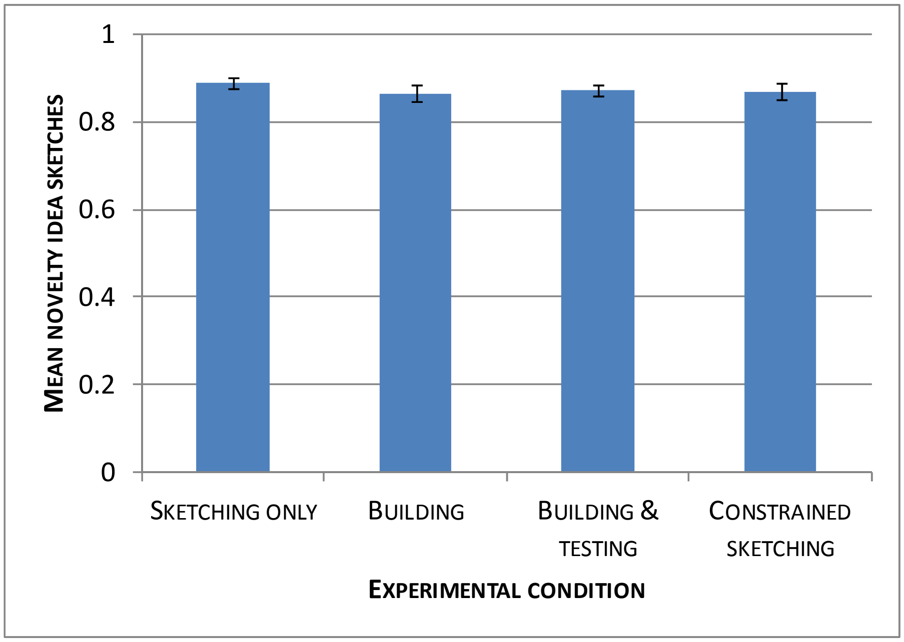


Figure 17: Mean novelty across the various conditions for the idea sketches, showing no significant difference (Error bars are (±) one standard error of the mean).

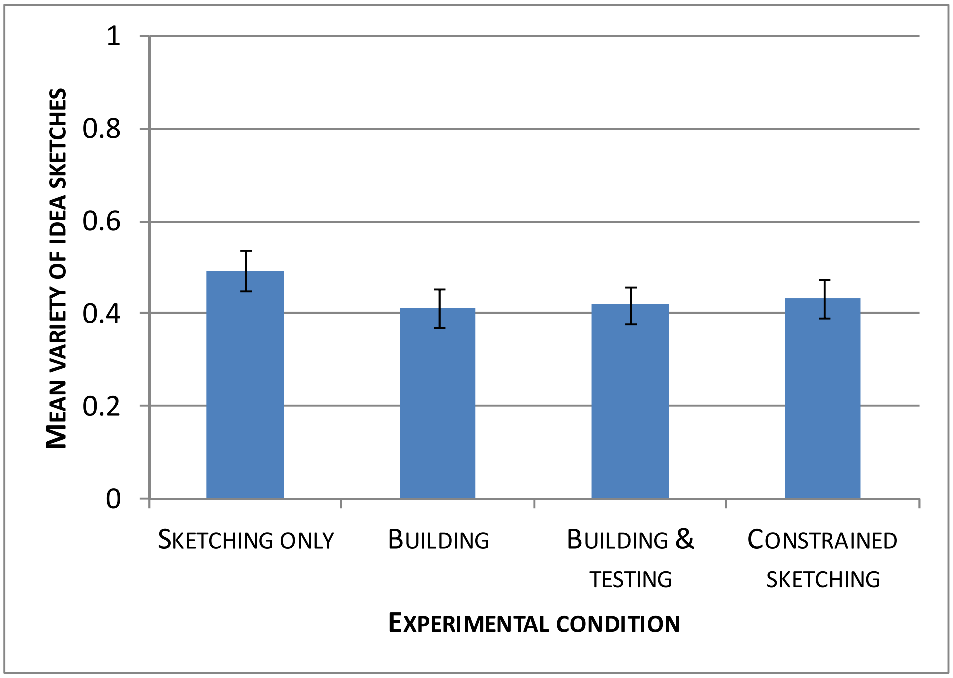


Figure 18: Mean variety across the various conditions for the sketches, showing no significant difference (Error bars are (±) one standard error of the mean).

Learning from Physical Models

The results from the Building & Testing condition supported the hypothesis that physical models supplemented designers' mental models. Still, these results did not support the argument that the participants learned quickly from the building process. In this case also, percentage of functional ideas was used for investigating the learning from physical models. It was observed that, after the Testing while Building Activity, when the participants sketched additional ideas, they created a lower percentage of functional ideas. If there was quick learning from physical models, the participants were expected to continue generating the same percentage of functional ideas in the Follow-up Sketching too. The percentage of functional ideas showed a significant difference across the Testing while Building and Follow-up Sketching activities in this condition (Figure 19). This difference was statistically confirmed using a t-test (t (1, 39) = 10.48, $p<0.001$, $MS_{error} = 0.48$). The mean percentage of functional ideas from the Follow-up Sketching Activity matched that from the Sketching Only Condition. This showed that physical modeling supplemented participants' mental models but did not initiate a significant amount of learning. When the participants were asked to sketch their new ideas later, they generated more non-functional ideas. Said observation supported the argument that, their mental models still contained errors and they did not learn quickly from building and testing physical models. The results from explained earlier in this section showed that the effect of time at which ideas are generated on the percentage of functional ideas was not significant enough to cause any bias.

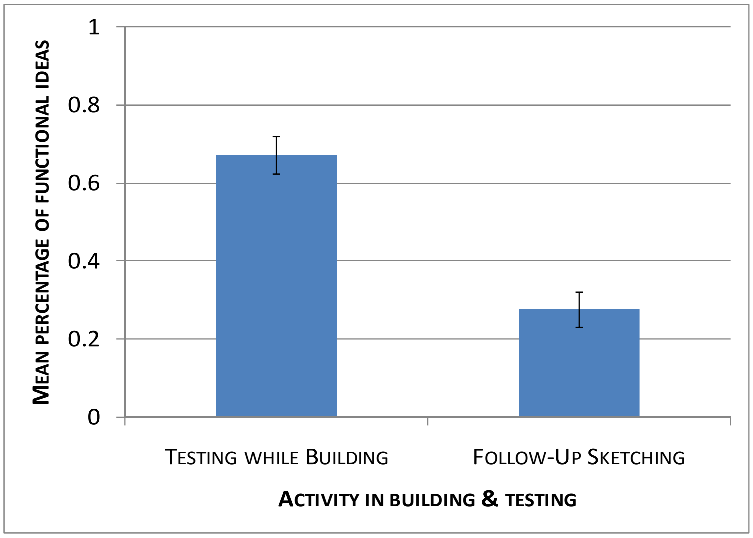


Figure 19: The mean percentage of functional ideas showed a significant difference between the Testing while Building and Follow-Up Sketching activities in the Building & Testing Condition (error bars are (±) one standard error of the mean).

Discussion

Effects of Physical Models on Mental Models

The variation between the percentages of functional ideas across the conditions strongly supports the Mental Model Hypothesis for novice designers. As revealed in the results, the percentage of functional ideas is significantly higher in the Building and Building & Testing conditions, compared to the Sketching Only Condition. The lower percentage of functional ideas in the Sketching Only Condition can be explained as a result of the designers' erroneous mental models, as design sketches often reflect the errors in designers' mental models. Due to these errors, a significant portion of the ideas do not satisfy the design problem requirements, leading to a decreased percentage of functional ideas. Conversely, when we allow the designers to build their ideas, they realize the flaws in their ideas and rectify them. This can explain the significantly higher percentage of functional ideas in the Building conditions. Said conclusion might also hold true in the case of the Building & Testing Condition. Here, the percentage slightly increases because the participants test their ideas more thoroughly, allowing them to better judge the effectiveness of their ideas. If there are errors in their ideas, they gain the opportunity to recognize the errors and rectify them. Said results demonstrate that physical models might sufficiently supplement designer's mental models during idea generation.

This result agrees with prior literature that argues for the use of physical models in design. When designers build and test their ideas during idea generation, they can easily detect the shortcomings of their designs and eliminate them. Consistent with the findings of this study, the studies by Kiriyama and Yamamoto [15], Acuna and Sosa [75], Horton and Radcliffe [67] and the arguments of Kelley [9] and Bucciarelli [70] demonstrate that, as designers build their ideas, they reduce the risk associated with innovation.

Effects of Physical Models on Design Fixation

Contrary to our expectations, based upon research, this study does not show that physical models cause fixation. Both novelty and variety show no significant difference across the conditions. The prior observational study by Kiriyama and Yamamoto [15] reports that building physical models decreased the variety of ideas. In that study, designers solve a design problem which is much more complicated than the paperclip problem utilized in this study. Contradicting the Kiriyama and Yamamoto study, Youmans [16] observes that, when designers build their ideas, they replicate fewer features from the example provided to them, indicating decreased design fixation. These conflicting results corroborate the importance of design problem complexity to design cognition. If the design problem is more complex, designers spend more time, money and effort to solve it. Considering these issues, we need to further investigate the effect of the design problem complexity on the novelty and variety of ideas.

One potential explanation for the observed conflicting results [41, 47] is the Sunk Cost Effect . The Sunk Cost Effect, as explained in Chapter II, refers to an adhesion to a selected course of action in fear of losing resources already invested in that course. This theory explains that, if the cost sunk into a course of action is high, a person is more likely to stick to that course even if it is more logical to choose a different course of action. A typical example of this is gambling. The probably of any outcome is always the same but it is hard to quit once there is a sunk cost. Instead, a person's decisions about future should be based upon the anticipated costs associated with the paths, not the already sunk cost. In design, resources include time, money or effort. When solving complicated design problems using physical models, designers spend a significant amount of time and effort building prototypes. Due to the Sunk Cost Effect, they might be extremely reluctant to choose another idea which is drastically different from their current conception; and thus they appear to be fixated. In this study, because sunk cost is very low, it is easy for the designer to generate drastically different ideas without sunk cost having an effect. This leads to lower fixation. Hence it can be argued that the design fixation observed in the said prior studies with more complicated design problems is due to Sunk Cost Effect and fixation is not inherent in physical modeling.

The previous argument concerning the Sunk Cost Effect is supported by the conflicting results from the various studies. The current results and the results from the study by Youmans [16] fail to show any fixation caused by physical models during idea generation. At the same time the observational studies by Kiriyama and Yamamoto [15] and Christensen and Schunn show that designers building their ideas for comparatively complicated design problems tend to fixate. The difference between the results of the controlled and observational studies can be explained in terms of the Sunk Cost Effect. When designers tend to fixate to example features, the building process can break the fixation, as suggested by Youmans' results. Likewise, as the complexity of the design problem increases, physical models tend to fixate designers to their initial solutions, as suggested by the Sunk Cost Effect. To clarify this issue, these explanations require further investigation.

Eliminating Experiment Biases

Additional activities and analysis eliminated possible experimental biases that could provide alternative explanations for the results. This study investigates the time at which ideas are generated, implicit constraints associated with the building materials and processes and the differential building skills of the participants, but none of these factors significantly affect the metrics.

It is observed that the time at which the ideas are generated and designers' building skills possess little effect on design cognition with physical models. The percentage of functional ideas shows a slight decrease as time progresses, but this decrease is not significant and is independent of condition, i.e. it does not significantly interact with condition. If time is a significant factor, since it is faster to sketch an idea than to build one, the authors need to account for time in the experimental design. It is also observed that the percentage of functional ideas does not vary significantly with the building skills of participants. Consequently, the building skill of the participants is ruled out as a factor in the analysis. The controllability of these two factors is, in these experiments, extremely low.

The Constrained Sketching Condition attempts to separate any possible cognitive effects, during the idea generation process, of implicit constraints from that of physical representations. In this condition, designers are aware of the constraints due to available materials, but are not able to build their ideas. Compared to the Sketching Only Condition, the Constrained Sketching Condition leads to a higher percentage of functional ideas. This shows that the implicit constraints associated with the building process and materials have some effect on the physical modeling idea generation process. Likewise, the Building and Building & Testing conditions lead to even higher percentages of functional ideas. This demonstrates that, though constraints have some influence on designer behavior, they are not entirely responsible for the differences in the percentage of functional ideas. As a result, building prototypes potentially supplements designer’s mental models and might increase the percentage of functional ideas.

Learning Effects from Physical Models

The significant difference between the Testing while Building and Follow-up Sketching activities in the Building & Testing Condition provides a striking insight concerning the use of physical models in idea generation. Surprisingly, the percentage of functional ideas in the Follow-Up Sketching Activity is significantly lower compared to the Testing while Building Activity. Though this comparison cannot be a pure test of learning, these results indicate that designers may not quickly learn, i.e. cause their mental models to change, as a result of the physical modeling process [94, 95]. If there is a significant change in the designer’s mental models of how the wire behaves, the percentage of functional ideas needs to remain constant between these activities; the results do not confirm this. Therefore, one might determine that physical modeling helps designers to improve the quality of their ideas, but it does not help them quickly improve their mental models. This result agree with findings from the field of education which say that changing mental models cannot be instantaneous; rather, mental model development is a gradual and time consuming process [94, 95].

In order to generalize these results to a larger population, including expert designers, more experimentation needs to be done. The participants in this work are primarily senior undergraduate students. It would be interesting to investigate how expertise in solving open-ended problems plays a role in the cognitive effects of physical modeling. Several previous studies in design have shown that the behavior of experts and novices vary during the idea generation process [13]. They show that, although both experts and novices tend to fixate to features of example solutions, experts can easily mitigate this fixation by using defixation materials. Defixation materials are not effective in novices. It would be interesting to see how the use of physical models affects the idea generation behavior of experts compared to novices.

This study needs to be repeated with different design problems to check the generalizability of the observations. Given that many mental model errors are observed while solving a simple design problem in this study, more errors can be expected in complicated design problem solving. As a result, physical models can be more useful in such cases.

Conclusions

Since engineering idea generation is a crucial part of new product development, techniques for idea generation need to undergo careful study. There is little empirically based guidance in the literature on when physical representations should be implemented in the design process. This paper investigates the use of physical models in the idea generation process and their impact on the quality of designs produced.

A between-participants, controlled experiment is presented in this chapter. This experiment evaluates two hypotheses: physical models cause design fixation and they lead to higher quality ideas by supporting designer's mental models of the physical world. The results indicate that novice designers using physical models as a tool for idea generation create significantly higher percentages of functional ideas compared to those who only sketch. This indicates that the use of physical models helps to rectify the flaws in a designer's mental models, leading to an increased probability of functional idea creation. No evidence for design fixation is observed in novice designers. The novelty and variety of ideas was similar across all conditions.

Another interesting result obtained from the Building & Testing condition relates to the potential improvement of designers' mental models from physically modeling their mental conceptions. Once designers use physical models, their mental models should improve. The data from the Follow-up Sketching Activity, which occurs after participants spend time building, does not indicate that the designer's mental models improve. To put it another way, there are no immediate impacts on learning.

CHAPTER IV

EFFECT OF SUNK COST ON DESIGN FIXATION – THE SUNK COST EXPERIMENT

The disparity between the result of the study explained in Chapter III and the prior observational studies [15, 96] might be explained by the Sunk Cost Effect [41, 97]. The prior studies use more complicated design problems and building physical models for them takes more time and greater effort than the paperclip design problem. Hence the sunk cost associated with those studies is greater. Based on this disparity, this study hypothesizes that design fixation is caused by the Sunk Cost Effect and is not inherent in physical modelling. The Mental Models Hypothesis tested in Chapter III is also reaffirmed using this study.

Hypotheses

Based upon the background research explicated previously, the study in this chapter attempts to resolve the veracity of two hypotheses:

Sunk Cost Hypothesis: Building physical models with higher associated sunk cost lead to greater amount of design fixation.

Mental Models Hypothesis: Physical models supplement designers' erroneous mental models, leading to a higher percentage of functional ideas. They help designers identify and correct errors in their design concepts caused by erroneous mental models.

To evaluate these hypotheses, a between-subject, controlled laboratory experiment is designed and conducted. The subsequent sections present the overall procedure, interpretations of the results and a general conclusion.

Method

Evaluation of the hypotheses occurred via a between-subject controlled laboratory experiment conducted at Texas A&M University. The experiment included five conditions: Sketching Only, Metal Building, Plastic Building, Metal Constrained Sketching and Plastic Constrained Sketching. In each condition, the participants received the same design problem, only the mode of representation used to generate solutions differed. The title of each condition designated the type of representation utilized for idea generation. Building conditions allowed the author to infer the effects of the building process and sunk cost on designer cognition. Similarly, the constrained sketching conditions isolated the effects of the implicit constraints of the building process and materials.

According to the Sunk Cost Hypothesis, designers generating ideas using higher cost representations fixate more than those who use representations with lower sunk cost (e.g., Plastic Building instead of metal). Building the physical model of an idea out of plastic takes considerably longer than with metal. Resultantly, the plastic building process involves a greater sunk cost. Consequently, higher fixation is expected in the Plastic Building condition compared to the Metal Building condition. From the study in

Chapter III, one observes that the use of steel wire to build physical models of ideas does not illicit significant fixation relative to the amount of fixation associated with sketching. Metal Building does have a slightly higher sunk cost than sketching, but the difference may not have been substantial enough to cause statistically significant differences in the data in the previous study. The average novelty and variety of ideas generated by participants remained the same across the Sketching Only and Metal Building conditions. Since the Plastic Building Condition is associated with a much higher sunk cost, the author anticipates that the Plastic Building Condition should cause greater design fixation, yielding significantly lower novelty and variety compared to the Sketching Only and Metal Building conditions.

Building physical models with plastic differed from that with metal in one other aspect: the scale of the models. Before the start of the experiments, a majority of the steel physical models created by the participants in the prior controlled study (Chapter III) were rebuilt by an independent judge using plastic. It was verified that more than 90% of those ideas could be built using plastic, but on a larger scale. Due to this reason, in the Plastic Building Condition, the participants were instructed to scale their physical models if they wished.

Constrained sketching conditions should facilitate the inference of the idea generation effects of the implicit constraints associated with the building process. Any effect observed in the study could be due to a combination of these constraints and the building process itself. In the constrained sketching conditions, the participants received the necessary training for building before sketching their ideas. During the training for building, they familiarized themselves with the materials and processes used, making them aware of the constraints associated with the building materials and processes. For this reason, as in Chapter III, any effect observed in the constraint sketching conditions might highlight the contribution of implicit constraints.

The design problem involved creating an object to bind ten sheets of paper together without damaging the paper. Just as in the study outlined in Chapter III, the design problem was the same for each condition. The participants in the metal building condition were told that the object needed to be built out of no more than 9" of steel wire. Correspondingly, the participants in the plastic building conditions were told that the object should be moldable of plastic. Each group was instructed to generate as many solutions as possible for the design problem. Moreover, each participant was told that they could utilize the duration of the experiment to generate solutions. They were not told of a time limit, but each participant was not allowed to quit the idea generation component until the end of the allotted time.

Table 3 shows the time allotted for idea generation in each condition. As in the study from Chapter III, the participants were encouraged to generate non-conventional and technically infeasible ideas, because any idea might lead to implementable, novel solutions. Similarly, they were also encouraged to sketch any ideas which could not be built from the provided materials. To indicate their infeasibility, the participants were instructed to mark these ideas with an "X"" next to the sketch to set them apart from the rest.

Table 3. Time limits for various activities in the experiment

Condition	Activity	Max time (Hrs:Min)
Sketching Only	Idea generaion with sketching only	1:45
	Building	0:30
	Testing	0:10
Metal Building	Idea generation with building	2:20
	Testing	0:10
Plastic Building	Idea generation with building	2:20
	Testing	0:10
Metal Constrained Sketching	Idea generaion with sketching only	1:45
	Building	0:30
	Testing	0:10
Plastic Constrained Sketching	Idea generaion with sketching only	1:45
	Building	0:30
	Testing	0:10

Participants

A total of 112 participants volunteered to take part in the experiment. Out of these, one participant had participated in a previous experiment with the same design problem and another participant was a Psychology major. Consequently, data from these participants were not included in the analysis. The rest of the participants were distributed randomly across the five conditions. Each condition had 22 participants each with 18 senior undergraduate and 4 graduate students from Texas A&M University. The students were recruited from design classes offered by the Mechanical Engineering Department at Texas A&M University or through posted flyers (eight participants). They were offered extra credit or monetary compensation for participating in the experiment. The participants were instructed not to discuss any aspects of the study with other students to avoid bias. A survey at the end of the experiment determined if the participant possessed prior exposure to the design problem. One to four participants were run through the experiment simultaneously. In the experiment, the average age of the participants was 23, with 17 being female.

Tools and Materials

The participants were provided with the tools and materials necessary to create prototypes of their ideas as determined by the condition described in detail below. They were given necessary training on the use these tools and materials in the form a recorded video with a narration by a native, English speaker.

To build physical models out of steel wire, the participants received the tools and materials shown in Figure 20. They also possessed a mechanical press, allowing them to cold work their models to preserve their shapes. They were provided with steel wire pieces, each nine inches long. The diameter and the stiffness of the wire provided to the participants were chosen to ideally make physical models. The length of the wire was restricted to 9 inches to avoid participants making tray-like ideas, as observed in prior preliminary pilot studies . Since these solutions require a significant amount of time to build, their discouragement was desirable to enable the participants to produce a maximum number of solutions during the three hour experiment. At the end of the idea generation, the participants were provided with ten sheets of paper to test their ideas.

In conditions where participants built physical models of their ideas out of plastic, the participants were provided with the plastic in pellet form. This plastic was easily moldable by heating it in water and then placing the warmed plastic in a mould of suitable shape. The participants were provided with a hot plate and a heating pan to accomplish this. They were also provided with mould putty and necessary carving tools to create their moulds in the required shapes. These tools and materials are shown in Figure 21. As in previous conditions, at the end of the idea generation, the participants were provided with ten sheets each of paper and cardboard. In many cases, participants built scaled up models with plastic, because they could not make their ideas both thin and stiff simultaneously. The card board pieces helped participants test their scaled-up models. When the participants scaled up their models, the models were unable to hold ten sheets of regular paper as the models were too big for them. In these cases, they were able to test their ideas using card board pieces.

Figure 20: Tools and materials used for making physical models out of steel wire in Metal Building and Metal Constrained Sketching conditions

Figure 21: Tools and materials used for making physical models out of plastic in Plastic Building and Plastic Constrained Sketching conditions.

Procedure

All seats were separated from each other using dividers or curtains so that the participants could not see each other. Participants were randomly assigned to a condition as they entered. The experiment began with consent and all the participants were requested to refrain from discussing any aspect of the study with their friends or classmates. After consent, in the Sketching Only condition, the participants were directly given the design problem to solve. In all other conditions, the participants first watched the training video and were then given the design problem. Their pens were exchanged at regular intervals to keep track of the time at which an idea was generated. At the end of idea generation, participants were asked to test their built models and mark the functional ones. The procedure followed for each condition is described in detail below.

Sketching Only Condition

In this condition, participants spent the majority of their time sketching their ideas. At the end of the sketching activity, they were asked to build prototypes of their ideas. In this condition, 50% of the participants built their ideas using steel wire and the remaining used plastic. After the building activity was completed, the participants were given ten sheets of paper to test their ideas. For the participants who built their ideas with plastic, a few pieces of card board were also provided to test the scaled-up prototypes. Once the testing was completed, the participants were asked to mark the ideas they had seen before. They were also asked to sketch examples of paperclips that they had seen before, other than the ones they already sketched. The experiment ended with a survey, which collected information about their perception of various activities in the experiment, their prior exposure to the design problem, their comments about the experimental setup and some biographical information.

In this condition, the time allotted for building the physical models was much smaller than that of sketching, due to experimental time limitations. Hence some participants were unable to finish building their ideas. For such participants, two independent reviewers built the ideas separately and tested them. A Pearson's correlation of 0.97 and Cohen's Kappa of 0.94 were obtained for the test results, showing a satisfactory inter-rater agreement for the functionality of these ideas.

Metal Building Condition

In this condition, the participants were allowed to sketch their ideas and build physical models of with steel wire. The experiment began with a recorded training video explaining the use of various tools and materials. Then the participants were asked to sketch as many ideas as possible to solve the design problem and build physical models of their ideas. Figure 22 shows examples of models generated by participants. Idea generation was followed by a testing activity, in which the participants tested their ideas with ten sheets of paper. Similar to the Sketching Only Condition, participants were also asked to identify the ideas that they remembered seeing before. This condition also ended with the survey.

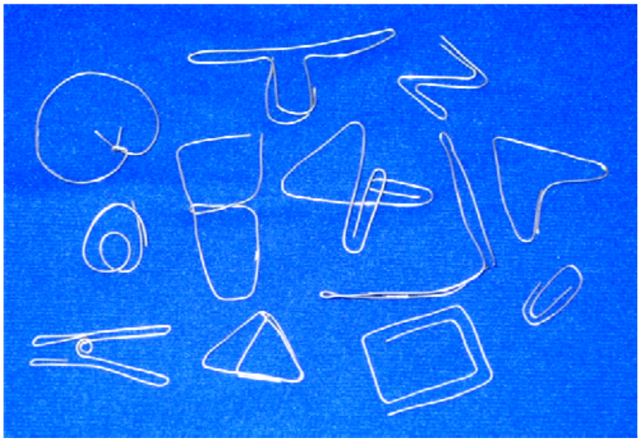


Figure 22: Examples of steel paperclips built by the participants

Plastic Building Condition

This condition was identical to the Metal Building Condition, except that participants built the physical models of their ideas out of plastic. Figure 23 shows examples of models built by participants out of plastic. They were also provided with cardboard to act as a scaled up version of paper.

Figure 23: Examples of plastic paperclips built by the participants

Metal Constrained Sketching Condition

This condition was identical to the Sketching Only Condition except that the participants were informed that they would build physical models of their ideas out of steel wire before they began sketching. Also, they were shown the training video prior to sketching ideas. Following idea generation, they built their ideas from metal just like the Metal Building Condition. All other activities remained the same as in the Sketching Only Condition.

Similar to the Sketching Only Condition, two independent evaluators built and tested the models not completed by the participants. In this condition, a Pearson's correlation of 1.0 and a Cohen's Kappa of 1.0 were obtained.

Plastic Constrained Sketching Condition

This condition was identical to the Metal Constrained Sketching condition, except that the participants were informed that they would build their ideas out of plastic.

Again, two independent evaluators built and tested the incomplete models. A Pearson's correlation of 0.94 and Cohen's Kappa of 0.93 were obtained in this condition.

Metrics for Evaluation

As in the study elucidated in Chapter III, three expert judgement rating scales are used for this study: Novelty, variety and percentage of functional ideas. To the ensure reliability of these measures, two independent judges are asked to analyze the data. A high inter-rater agreement between the two reviewers proves the consistency of the analysis and the reliability of the measures [92].

Measurement of Design Fixation and Sunk Cost Effect

Variations of the novelty and variety metrics from Shah et al. are utilized to measure design fixation [87, 91, 98]. In this study, the novelty and variety data were processed and analyzed in a manner congruent to that used in the study described in Chapter III.

In order to ensure the reliability of the novelty and variety measures, an independent reviewer sorted 55% of the sketches. This independent evaluator knew nothing concerning the conditions of the experiment and received no special instructions for sorting. Still, the second reviewer is asked to create approximately the same number of bins as the first reviewer. Since variety is determined as the ratio of the number of bins a participant's ideas occupy to the total number of bins, a significantly different number of bins from the two reviewers can bias the values of variety based on the bins. The independent evaluator is totally unaware of the results from the first sorting. An inter-rater agreement of 0.71 is obtained for novelty and 0.73 for variety. As these values are below 0.80, it is concluded that there is an inconsistency in the sorting by the two evaluators [92].

The low inter-rater agreement obtained from the sorting of the sketches might be due to the inherent ambiguity of sketches. In many cases, the functionality of ideas is not clear from the sketches and multiple interpretations are possible. In order to eliminate bias, the sorting process is repeated with the physical models. To clarify the functionality of the physical models, the models are attached to papers before sorting. Under these circumstances, an inter-rater agreement of 0.83 is obtained for novelty and 0.86 for variety. Said findings indicate that the method utilized in this study reliably calculates novelty and variety. Still, some participants sketch ideas which are not possible to build with the materials and tools provided. The sorting of built models cannot account for such ideas. As a result, the novelty and variety measures obtained from the sorting of sketches are reported as primary results. The data from the sorting of physical models are also presented to complete said results. Reinforcing the reliability of the method, in more than 99% of cases, an idea sketch and the corresponding physical model go to the same bin.

To measure fixation accurately, participants should run out of ideas within the provided amount of time. This helps eliminate bias due to differences in time required to generate ideas using the different methods. If the participants run out of ideas within the given time frame, this biasing factor can be eliminated. Interestingly, it is observed that, even for this simple design problem, participants do not run out of ideas. Accordingly, the time at which ideas are generated is tracked and its effect on the evaluation metrics is separately studied.

Differences in the variety or novelty across conditions would indicate design fixation. The study described in Chapter III shows no difference in novelty and variety across the Sketching Only and Building Conditions. The Sunk Cost Hypothesis proposes that this is due to the lower sunk cost associated with building ideas out of steel wire. If this is true, a relatively significant difference in the novelty and variety should be observed in the Plastic Building Condition due to its higher sunk cost. Building models with plastic takes comparatively longer than with metal. Nevertheless, it was verified that over 90% of the paperclips in this experiment built with metal wire could also be molded out of plastic. In other words, the type of material should not bias the type of ideas generated.

Measurement of Effects on Designers' Mental Models

The percentage of functional ideas metric measures the effects of the experimental conditions on participants' mental models. Consistent with Chapter III, a functional idea is defined as an idea that satisfies all the design problem requirements. The percentage of functional ideas for a participant is calculated as the ratio of the number of functional ideas generated to the total number of ideas generated by that participant. If designers' mental models are erroneous, their ideas may also contain errors. The percentage of functional ideas gives us a measure of the percentage of mental models that meet design requirements. Since sketching is the fastest medium for designers to externalize their mental models, ideas generated in the Sketching Only Condition can act as representatives of said mental models. Comparing the other conditions to the Sketching Only Condition, the author can infer the effect which the experimental conditions have on participants' mental models.

In order to measure the percentage of functional ideas, the participants are asked to judge the functionality of their ideas and mark the functional ideas during the testing activity. The functionality of the ideas is also judged by a second reviewer. To ensure the reliability of reviews, an inter-rater agreement is calculated between the two raters. A satisfactory Pearson's correlation of 0.93 is obtained for this, ensuring the reliability of this measure. Supplementation of erroneous mental models can lead to an increased number of functional ideas. For this reason, if physical models help supplement designers' mental models, as proposed by the Mental Models Hypothesis, building ideas should help participants generate a greater quantity of functional ideas. As a result, higher percentages of functional ideas are expected in the building conditions as compared to the Sketching Only Condition.

The constrained sketching conditions attempt to isolate the effects of the implicit constraints of the building materials and processes on designers' mental models. In these conditions, since the participants receive the necessary building training at the beginning of the experiment, they should be aware of the implicit constraints imposed by the tools and materials. If constraints influence idea generation, the percentage of functional ideas should be different in the constrained sketching conditions as compared to the Sketching Only Condition. In this metric, any difference between the constrained sketching and the building conditions provides a measure of the additional building effects over the associated implicit constraints.

Results and Discussion

This section presents the results obtained for the metrics mentioned in the section above. The metrics evaluating each hypothesis are separately presented along with their statistical analysis and a discussion of the results.

Sunk Cost Effect Hypothesis

To evaluate the Sunk Cost Hypothesis, novelty and variety metrics are analyzed. Comparing these metrics across the experimental conditions provides insights concerning the presence of the Sunk Cost Effect in design problem solving. Detailed analysis of the results is depicted in the sections below.

Analysis of Novelty

The mean novelty of sketched ideas varies significantly across the experimental conditions. Figure 24 shows this variation of mean novelty across the conditions. It is observed that the mean novelty of the building conditions is lower than that of the Sketching Only Condition. Such an observation reveals the presence of fixation while building physical models. Between the two building conditions, the Plastic Building Condition yields a lower mean novelty as compared to the Metal Building Condition, indicating that the plastic building group is fixating more compared to the metal building group.

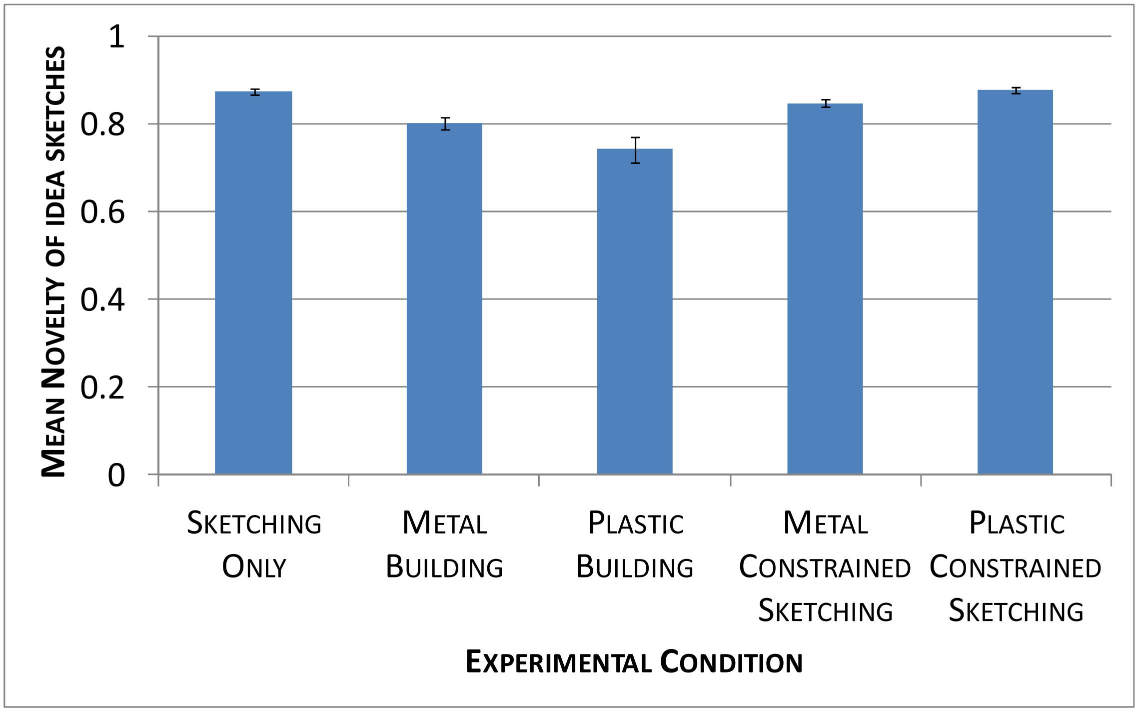


Figure 24: Variation of mean novelty of idea sketches across the experiment conditions. Error bars show (±) 1 standard error.

Since the novelty data do not satisfy the normality and homogeneity of variance assumptions required for an ANOVA, a permutation test equivalent to a one-way

ANOVA [99, 100] is used for statistical analysis. The results show that novelty varies significantly across the conditions (F (4, 105) = 12.75, p<0.001). Pair-wise permutation tests are used for a-priori comparisons [93] . The results of these a-priori pair-wise comparisons are shown in Table 4. Providing support to the Sunk Cost Hypothesis, these results show that the mean novelty of the Plastic Building Condition is significantly lower than that in the Metal Building Condition.

Table 4. A-priori comparison results for mean novelty of sketched ideas

Conditions Compared	p
Sunk Cost Effect	
Metal Building vs Plastic Building	0.08*
Effect of building on design fixation	
Sketching Only vs Metal Building	<0.001*
Sketching Only vs Plastic Building	<0.001*
Effect of implicit constraints on design fixation	
Sketching Only vs Metal Constrained	0.01*
Sketching Only vs Plastic Constrained	1.00

* statistically significant at $\alpha = 0.1$

The results from a-priori comparisons indicate that the implicit constraints associated with the building process, and the building process itself, affect the novelty of the ideas generated. In both building conditions, the mean novelty is significantly lower than the Sketching Only Condition, indicating that the designers fixate. Interestingly, the Plastic Building Condition yields a lower mean novelty compared to the Metal Building Condition. Said fact shows that participants who build their models with plastic fixate more compared to those who build with metal. These results provide strong support to the Sunk Cost Hypothesis. It is also observed that the Metal Constrained Sketching Condition stimulates lower novelty ideas as compared to the Sketching Only Condition, indicating that the implicit constraints associated with metal building fixate designers. Still, this does not happen with the implicit constraints associated with plastic building.

Sketches of ideas produced by the participants possess a certain level of ambiguity in conveying the functionality of the paperclip designs to the reviewers. Since they cannot build and test each design while sorting, the evaluators are forced to use their judgment to determine functionality. In order to eliminate any bias due to the ambiguity of sketches, the mean novelty scores are calculated for the physical models. Before sorting the physical models, the paper clips are attached to papers to demonstrate their functionality to the evaluators. The clarity of their judgment is evident from the differences in the inter-rater agreements reported in the metrics section. The sorting of idea sketches yields a low inter-rater agreement as compared to the physical models, showing that the idea sketches are ambiguous. Figure 25 shows the variation of mean novelty for built physical models across the experimental conditions. Contrary to the results for sketched ideas, it is observed that the mean novelty of built prototypes in the Metal Building Condition does not significantly differ from the Sketching Only Condition. Reinforcing the presence of the Sunk Cost Effect, the mean novelty is significantly lower for the Plastic Building Condition as compared to that in the Metal Building Condition ($p < 0.04$ from a permutation test). All other pair-wise comparisons follow the same trend as the sketched ideas. These results are consistent with the results from the study described in Chapter III.

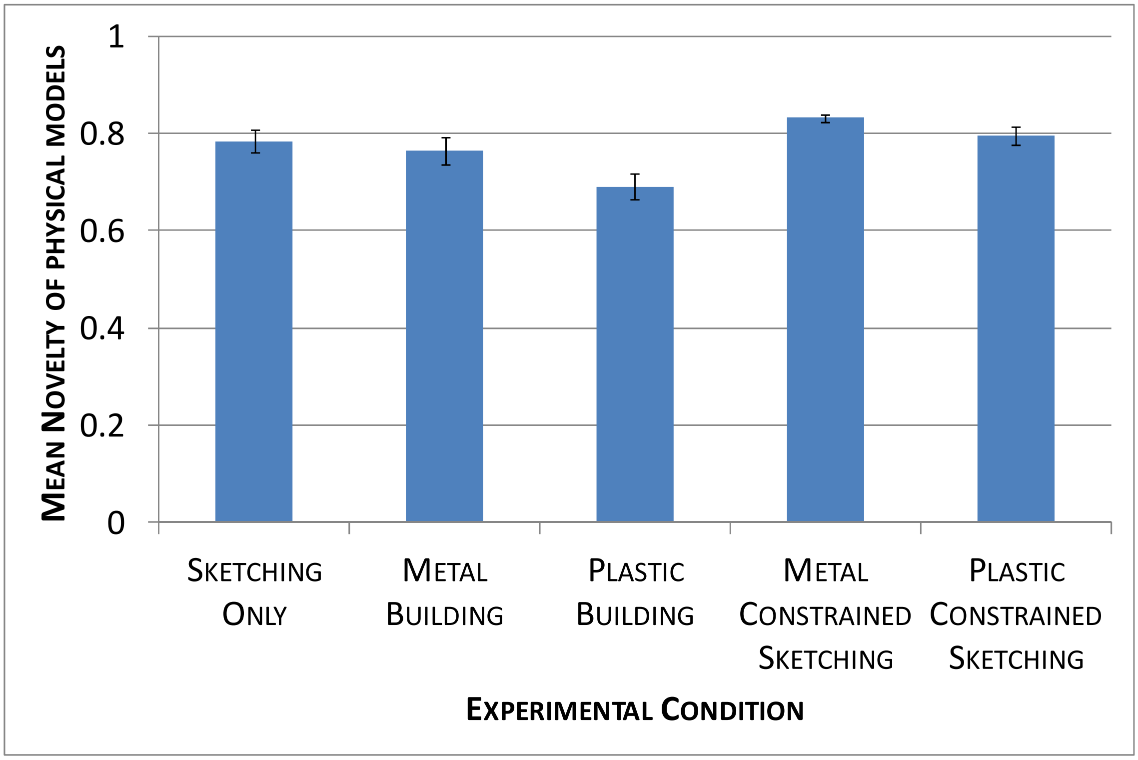


Figure 25: Mean novelty for built physical models across the experimental conditions. Error bars show (±) 1 standard error.

The mean novelty from the sorting of idea sketches shows that designers building physical models with metal fixate. Interestingly, the mean novelty from the sorting of physical models does not support this. Said disparity might arise from the quantity of non-buildable ideas sketched by the participants. Comparing the novelty trends in

Figure 24 and Figure 25, one can observe that the mean novelty in the Sketching Only and Plastic Constrained Sketching Conditions increases for the sketched ideas as compared to the physical models. For all other conditions, the mean novelty remains the same. When participants sketch their ideas, occasionally they sketch ideas that include electricity, magnetism and other similar principles which are impossible to build using the available materials. As evident from Figure 26, the mean percentage of these non-buildable ideas is significantly higher in the Sketching Only Condition and the Plastic Constrained Sketching Condition, causing an increase in the novelty scores of those conditions. These non-buildable ideas are counted for the sorting of the idea sketches, but not for the sorting of the physical models. A resorting of the idea sketches for only the buildable ideas provides the same mean novelty pattern as the built models, showing that the variation in the pattern between sketches and models is caused by the non-buildable ideas.

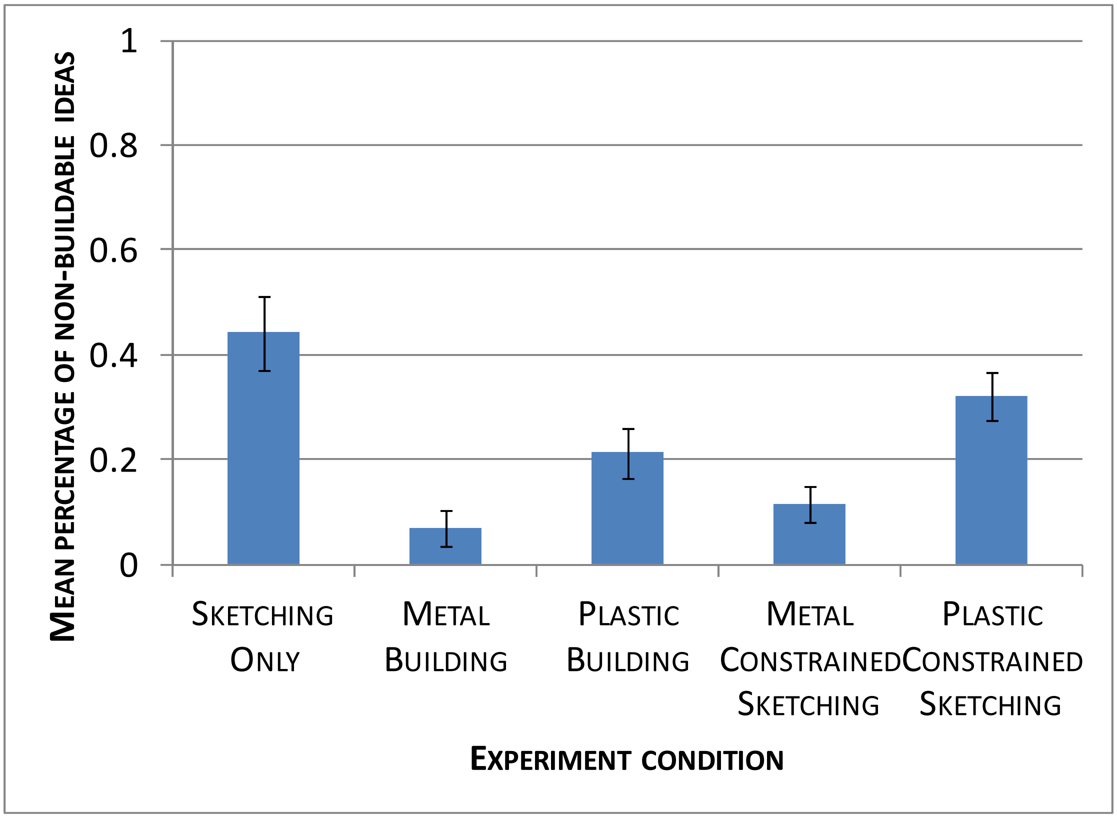


Figure 26: Mean percentage of non-buildable ideas across the experiment conditions. Error bars show (±) 1 standard error.

Analysis of Variety

As shown in Figure 27, the mean variety of sketched ideas also varies significantly across the experimental conditions. Similar to the mean novelty, the mean variety is lower for the building conditions as compared to the Sketching Only Condition. Nevertheless, the mean variety remains the same across the Metal Building and Plastic Building Condition, providing no support to the Sunk Cost Hypothesis. It is possible that the variety metric is not sensitive enough to detect differences.

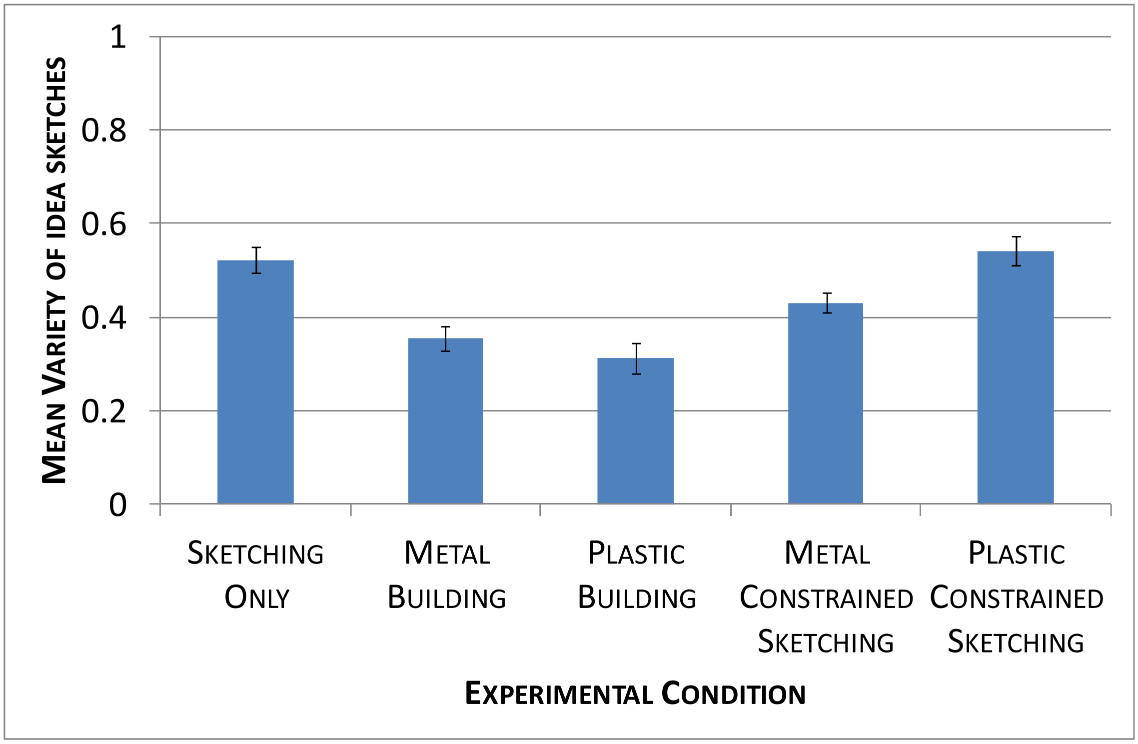


Figure 27: Variation of mean variety of idea sketches across the experiment conditions. Error bars show (±)1 standard error.

Using a one-way ANOVA, the variety results show an overall significance across the conditions (F (4, 105) = 13.13, p<0.001). Pair-wise t-tests are used for a-priori comparisons, and the results are shown in Table 5. The data are not normally distributed, but variance is homogeneous across the conditions. Since the sample size is large enough and all the conditions have equal numbers of participants, the data is robust to the violation of normality and ANOVA may be used. To confirm the ANOVA results, a permutation test equivalent to a one-way ANOVA is used and the obtained results are consistent with the one-way ANOVA.

Table 5. Pair-wise a-priori comparisons for the variety data

Conditions Compared	p
Sunk Cost Effect	
Metal Building vs Plastic Building	0.35
Effect of building on design fixation	
Sketching Only vs Metal Building	<0.001*
Sketching Only vs Plastic Building	<0.001*
Effect of implicit constraints on design fixation	
Sketching Only vs Metal Constrained Sketching	0.01*
Sketching Only vs Plastic Constrained Sketching	0.68

* statistically significant at $\alpha = 0.05$

From the a-priori comparison results, it is observed that the participants building their ideas produce a lower mean variety of ideas as compared to those who only sketch. This indicates that designers fixate as they build their physical models. Contrary to the results of novelty, no significant difference in mean variety is observed across the two building conditions. Unsupportive of the Sunk Cost Hypothesis, this shows that the participants in both conditions fixate to the same extent. The Metal Constrained Sketching Condition produces a significantly lower mean variety as compared to the Sketching Only Condition, showing that the implicit constraints associated with metal building do affect design fixation. Still, the implicit constraints associated with plastic building fail to produce any significant effect.

In order to eliminate any bias due to the inherent ambiguity of design sketches, the mean variety is calculated by the sorting of physical models also. Figure 28 shows the variation of the mean variety of built physical models across the conditions. In this case, the Plastic Building Condition produces a significantly lower mean variety compared to all other conditions. From these data, it can be concluded that only the participants building their physical models with plastic fixate. This result agrees with the prior study (Chapter III) and provides strong support to the Sunk Cost Hypothesis. The difference in the pattern of mean variety between the sketched ideas and the built prototypes can be attributed to the variation of the quantity of non-buildable ideas across the conditions. In this case also, a resorting of the idea sketches of buildable ideas provides the same trend of mean variety as in case of the built models.

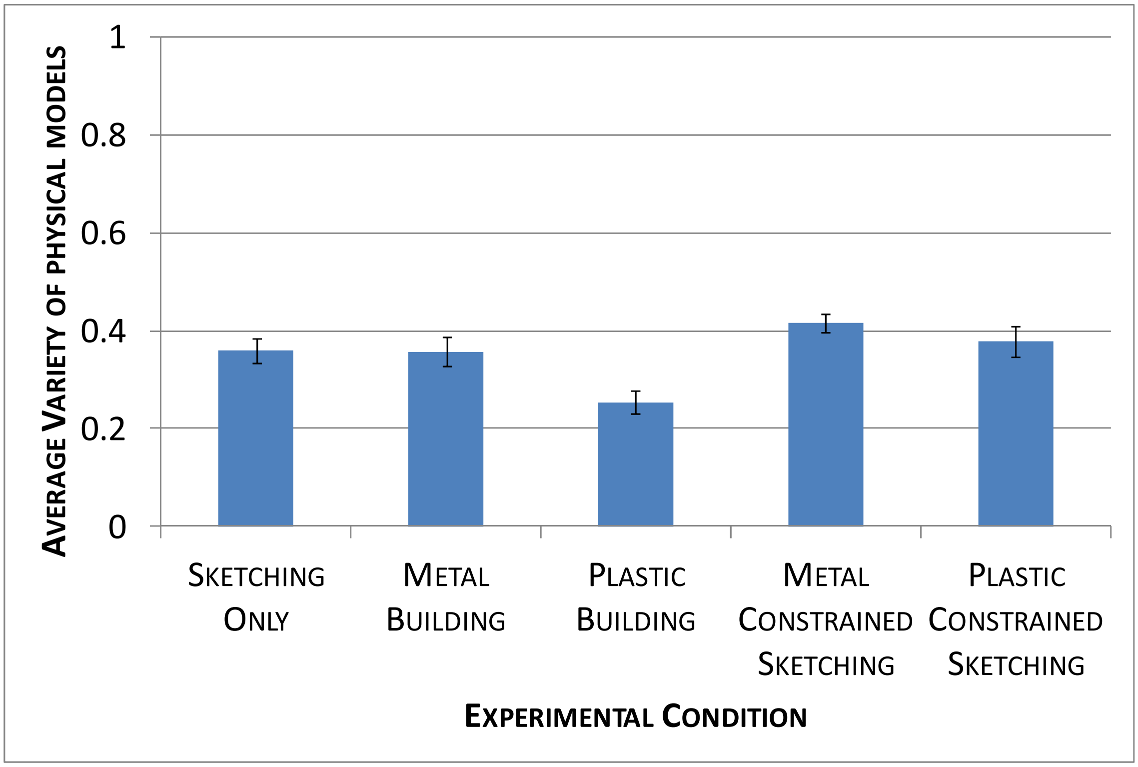


Figure 28: Variation of mean variety for built physical models across the experimental conditions. It is significantly lower for the Plastic Building Condition compared to other conditions.

Interpretation of Variety and Novelty Results

The variation of mean novelty and variety of idea sketches across the conditions indicates that designers tend to fixate as they build physical models of their ideas during idea generation. The Plastic Building Condition produces a lower mean novelty of idea sketches compared to the Metal Building Condition, indicating that designers fixate more as they spend more time on building. This result upholds the Sunk Cost Hypothesis. Even so, the mean variety of idea sketches does not follow this trend. The variation of the quantity of non-buildable ideas across the conditions might account for this difference. The Sketching Only and Plastic Constrained Sketching conditions produce significantly higher numbers of non-buildable ideas. Interestingly, the majority of these non-buildable ideas are very novel and as a whole they possess a diverse variety. Due to the effect of these non-buildable ideas, the mean novelty and variety scores of the said conditions increase, causing a variation from the trend of the built physical models. Reinforcing this argument, a sorting of the idea sketches for buildable ideas agrees with that of the built physical models. Said agreement strongly supports the Sunk Cost Hypothesis.

Another important insight from these results involves the effect, on idea generation, of the implicit constraints from the modelling materials. Both the mean novelty and variety measures, for idea sketches, depict a significant reduction from the Sketching Only Condition to the Metal Constrained Sketching Condition. In both cases, participants sketch their ideas throughout the entire idea generation process, but in the Metal Constrained Sketching Condition the participants are aware of the implicit constraints associated with the different materials. This causes them to fixate. Surprisingly, this result is not observed in the case of the Plastic Constrained Sketching Condition. This difference can be attributed to the variation of the quantity of non-buildable ideas across the conditions. The Plastic Constrained Sketching Condition produces a quantity of non-buildable ideas comparable to the Sketching Only Condition. Sorting the physical models and idea sketches for buildable ideas, one detects no significant difference in the mean novelty and variety between the Sketching Only Condition and the two constrained sketching conditions. This shows that, when only buildable ideas are considered, the implicit constraints do not fixate the designers.

Mental Models Hypothesis

Physical Models Improve the Quality of Ideas

Since the total number of ideas generated by the participants in each condition differs, percentages of functional ideas obtained from each condition are analyzed to evaluate the effects of building physical models on the quality of ideas generated. As shown in Figure 29, the data show significant differences in the percentage of functional ideas across the various conditions. The data are not normally distributed and not homogenous in variance across the conditions. As a result, a permutation test equivalent to a one-way ANOVA is used to analyze the data. The results show an overall significance for the model, ($F(4, 105) = 31.73$, $p<0.001$) meaning that the percentage of functional ideas varies significantly across the various conditions. Pair-wise permutation tests are used for a-priori analysis. Table 6 shows the results from these comparisons.

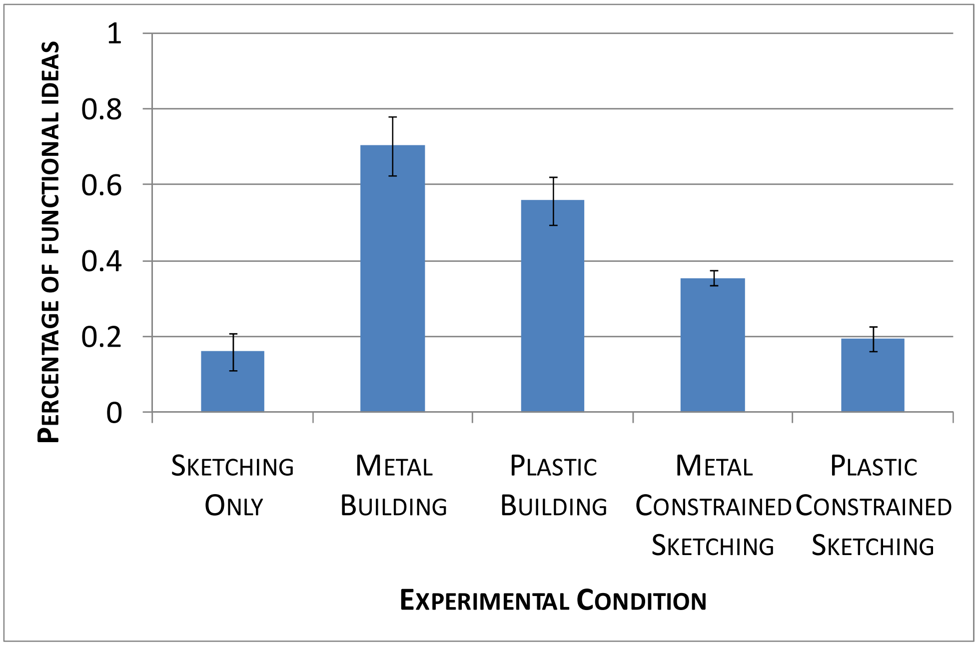


Figure 29: Percentage of functional ideas varies significantly across the conditions

Table 6. Pair-wise a-priori comparisons for the percentage of functional ideas

Conditions Compared	p
Effect of building on mental models (Metla Models Hypothesis)	
Sketching Only vs Metal Building	<0.001*
Sketching Only vs Plastic Building	<0.001*
Sunk Cost Effect	
Metal Building vs Plastic Building	0.02*
Effect of implicit constraints on mental models	
Sketching Only vs Metal Constrained	<0.001*
Sketching Only vs Plastic Constrained	0.41

* statistically significant at $\alpha = 0.05$

The results from a-priori comparisons show that, as the designers build their ideas, they generate a greater quantity of functional ideas. This result is consistent with the Mental Models Hypothesis. As designers build their ideas, they identify the shortcomings of their mental models and rectify them. This helps them to generate more functional ideas as compared to the Sketching Only Condition.

There is a significant improvement in the percentage of functional ideas in the Metal Constrained Sketching Condition as compared to Sketching Only Condition, showing that the implicit constraints associated with the building process and the materials have some effect on the functionality of the ideas generated. Nevertheless, the improvement observed in the mean percentage of functional ideas is not as significant as in the building conditions. In this case, the effects of the building process and the implicit constraints are present together. Consequently, the improvement in the mean percentage of functional ideas in the building conditions might result from a combination of the implicit constraints and the building process. These results show that, as designers build physical models of their ideas, they identify the flaws in those ideas and rectify them, leading to ideas of higher functionality. Thus, building physical models during the idea generation stage of design should be encouraged.

The significant difference in the mean percentage of functional ideas between the Metal Building and the Plastic Building conditions provides another interesting insight. Across these two conditions, the sunk cost of the building process varies. For this reason, this result shows that, when using a building method involving higher costs, designers tend to generate lower percentages of functional ideas. This indicates that building physical models with materials and processes that consume lower amounts money, time and effort can be beneficial in terms of functionality. In the end, the use of quick and simple physical models made of easily constructed and cheaply available materials can be extremely beneficial. This result is also in agreement with Yang's findings about a negative correlation between the time spent on physical modeling and the quality of the outcome for novice designers [77].

The quantity of non-buildable ideas, depicted in Figure 26, reinforces the Mental Models Hypothesis. It is observed that the mean percentage of non-buildable ideas is largest in the Sketching Only Condition, illustrating the extent of the erroneous mental models of designers in that condition. Interestingly, the mean percentage of non-buildable ideas reduces significantly when designers build their ideas. This shows that, as designers build their ideas, the physical models supplement their mental models, leading them to a lower mean percentage of non-buildable ideas.

The difference in the mean percentage of functional ideas across the Metal Constrained Sketching and the Plastic Constrained Sketching conditions is an unanticipated result. A pair-wise permutation test shows that this comparison is statistically significant ($F=41.16$, $p<0.001$). This result can be explained with the mean percentage of non-buildable ideas generated by the participants. From Figure 26, it is observed that the participants in the Plastic Constrained Sketching Condition generated a higher mean percentage of non-buildable ideas compared to those in the Metal Constrained Sketching Condition. These non-buildable ideas might account for the difference in the mean percentage of functional ideas between the two conditions. In both constrained sketching conditions, the participants receive building training before beginning idea generation. During the training, the participants can familiarize themselves with the implicit constraints of the building process and the materials. One might argue that, in Plastic Constrained Sketching Condition, the training time is not sufficient for the participants to familiarize themselves completely with the implicit constraints of the higher sunk cost building. As demonstrated by the Metal Constrained Sketching Condition, implicit constraints influence the mean percentage of non-buildable ideas. Consequently, the relative non-familiarity of participants with the implicit constraints associated with the Plastic Constrained Sketching Condition might lead to a higher mean percentage of non-buildable ideas.

Overall, one could argue that building physical models using a simpler building process is desirable. The lower associated cost can encourage a designer to develop a greater quantity of functional ideas. Another important factor might be the type of material utilized in the building process. Plastic forces designers to build scaled versions of a final prototype, but steel wire allows them to create full scale models. In the end, scaled prototypes might decrease the quality of a designer's solutions.

Eliminating Biasing Factors - Variation with Time

If the percentage of functional ideas varies with time, the fact that the Sketching, Metal Building and Plastic Building conditions require different amounts of time could impact the conclusion. Participants might generate better (functional) ideas first and then less technically feasible concepts in the latter portions of the experiment. To measure this, the time at which an idea is generated is tracked using pens of various colours. Figure 30 depicts the variation of the functionality of the ideas with idea generation time. A two-factor linear regression with interaction effects [101] between time and experimental condition is used to statistically verify the significance of time. An R^2 value of 0.82 is obtained for the model, showing that the fit is good enough to provide reliable statistical results. The overall regression model reveals statistical significance, ($F=24.83$, $p<0.001$) showing that the factors influence the functionality of ideas. Though time is observed to be a significant factor affecting functionality ($t=2.33$, $p = 0.02$), it does not interact with the experimental conditions to predict functionality ($t=0.88$, $p = 0.38$). The absence of any interaction shows that the effect of time on the functionality of ideas is uniform across the conditions. Such an observation enables one to independently analyze functionality across the conditions without taking time into consideration. Also, time accounts for only 14% of any observed variance in the mean percentage of functional ideas across any two conditions. Said fact eliminates the necessity to include time as a co-factor in the analysis of the percentage of functional ideas.

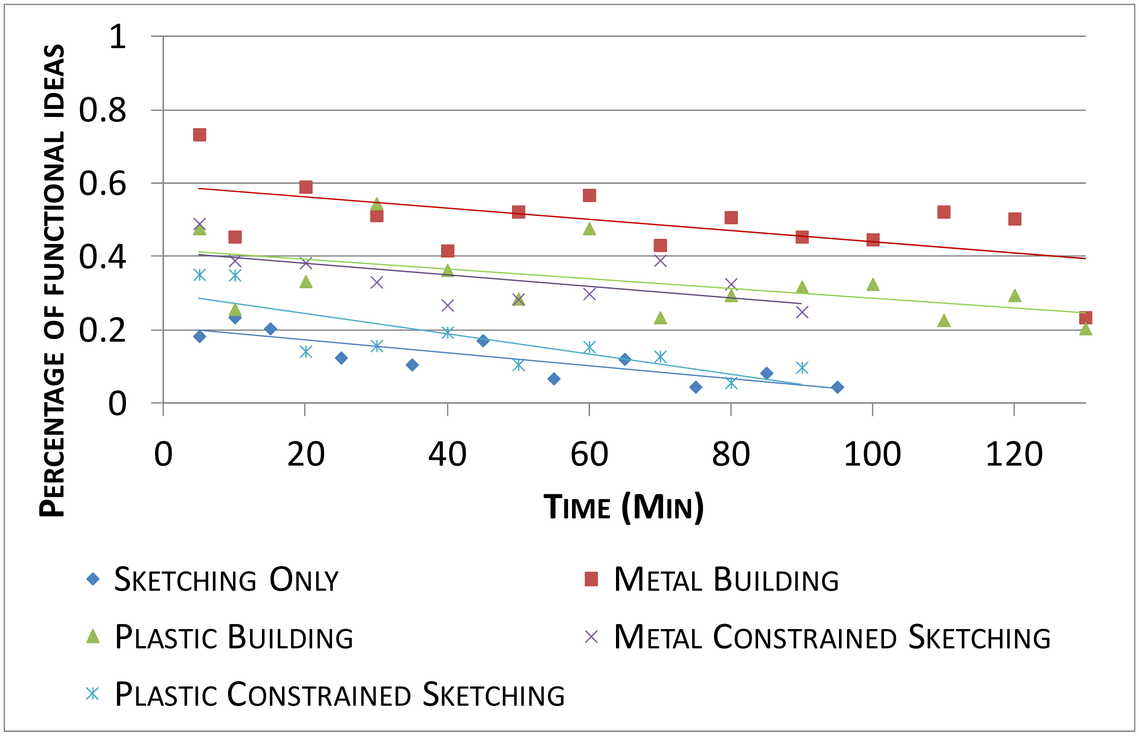


Figure 30: Percentage of functional ideas reduces slightly with idea generation time

Results from Post-Experiment Surveys

The post-experiment survey explored the opinions of participants about the representations that helped them to generate greatest number of ideas, greatest quality ideas and most functional ideas. The percentages of participants who chose different representations are shown in Table 7. Majority of the participants said that they generated most number of ideas during their primary idea generation task. However, they had mixed opinion about the representation that led them to greater quality ideas. These results also showed that the participants recognized that being able to build and test the physical models of their ideas leads them to most functional ideas.

Table 7: Percentage of participants selected various options in the post-experiment survey

Survey Question: Activity leading to greatest number of ideas idea			
Experiment Condition	**Activity**		
	Sketching	Sketching & Building	Testing
Sketching Only	80.00	12.00	8.00
Metal Building		95.65	4.35
Plastic Building		95.65	4.35
Metal Constrained Sketching	76.00	20.00	4.00
Plastic Constrained Sketching	90.91	4.55	4.55

Survey Question: Activity leading to the highest quality ideas			
Experiment Condition	**Activity**		
	Sketching	Sketching & Building	Testing
Sketching Only	62.50	20.83	16.67
Metal Building		81.82	18.18
Plastic Building		91.30	8.70
Metal Constrained Sketching	39.13	39.13	21.74
Plastic Constrained Sketching	52.17	21.74	26.09

Survey Question: Activity leading to the most functional ideas			
Experiment Condition	Activity		
	Sketching	Sketching & Building	Testing
Sketching Only	38.46	38.46	23.08
Metal Building		52.17	47.83
Plastic Building		61.54	38.46
Metal Constrained Sketching	29.17	41.67	29.17
Plastic Constrained Sketching	29.17	37.50	33.33

The post-experiment survey also instructed the participants to comment on the effect of various activities on their idea generation. Their comments are concatenated and classified into categories based on the common themes using a content analysis technique. The common comments are shown in Table 8. From the participant opinions it is clear that physical models lead them to identification of flaws in their designs and thereby to more functional ideas. Some participants also commented that building prototypes limited their creativity, which is consistent with design fixation. As future work, it will be interesting to study the actual ways that designers use physical models through protocol studies on them performing idea generation with physical models.

Table 8: Participant opinions about how the various activities affected the idea generation process

Activity	**Participant opinions**		
	Advantages	**Disadvantages**	**Other comments**
Sketching	Helped to visualize the design	Limited because sketching skill was not good	Did not affect
	Stimulated/improved ideation/brainstorming	Decreased my creativity	
	Inspired other designs	Limited by lack of prototyping	
	Increased creativity		
	Helped to prototype later		
	Troubleshooting/Helped detect design		
	Helped in general (no specific comments about how)		
Building	Revealed design/manufacturing difficulties	Limited creativity	Did not affect
	Made consider material properties	Forced to generate only functional ideas	
	Helped to refine details from sketch/better understand idea		
	Helped to generate more functional designs		
	Stimulated more ideas		
	Validated design assumptions		
Testing	Helped to determine functionality/feasibility	Limited idea generation	Did not affect
	Helped me refine ideas		
	Inspired to generate more ideas		
	Helped in general (no specific comments about how)		

General Discussion

The results from this study strongly support the concept that sunk cost influences engineering idea generation. When the associated sunk cost is low, the data show that the benefit of building physical models during idea generation might increase. Sunk Cost Effect is responsible for the design fixation observed in prior observational studies [15, 96] where designers generate ideas with the help of physical models. Those studies employ problems which are more complex than the paperclip design, resulting in a higher sunk cost associated with the building process. Ultimately, design fixation is not an inherent aspect of physical modelling, and it can be effectively mitigated via processes and materials with low associated costs.

The presence of sunk cost effects in engineering idea generation holds important implications for engineering design. Boujut and Blanco's argument for easily modifiable externalizations of ideas agrees with the findings of this study [58]. From their observational study on the mechanical design of the front axle of trucks, they show that less editable visualizations tend to fixate designers to initial ideas. These results highlight the necessity of building physical models with materials requiring minimum effort. Wong [102] argues that spending more time creating prototypes leads designers to commit to particular ideas. Said commitment decreases the responsiveness of designers to critical feedback regarding the prototype. Similarly, Yang [77] observes that spending less time fabricating a design correlates positively with the quality of the final product.

Based upon the previous arguments, faster prototyping techniques requiring a minimum amount of effort and cost need to be promoted. Considering this fact, rapid prototyping stands out as a good candidate for building physical models. Another possibility involves separating the physical model construction and ideas generation stages. The person generating ideas can provide the details of those ideas to a second person who can build the physical models and provide the model to the designer. This will eliminate any cost effects associated with physical modeling.

Conclusions

Physical models are widely implemented in engineering design. Though their use in design is encouraged by many researchers, some argue that models can lead to design fixation. Even so, the available guidelines detailing the usefulness of prototyping as a design tool are highly conflicting and do not properly lead designers to discover the highest quality solutions. This study provides useful insights concerning the influence of physical models in design cognition. Two hypotheses are tested using a controlled between-subject experiment. The first hypothesis states that the fixation present in idea generation with physical models is due to the Sunk Cost Effect and is not an inherent aspect of physical representations. The second hypothesis states that physical models supplement designers' mental models, leading to more functional (higher quality) ideas. The data clearly support both the hypotheses. The results show that allowing designers to build physical models of their ideas can significantly improve the quality of said ideas. The results also indicate that decreased designer effort during the building processes (such as quick models and rapid prototypes) is more beneficial because it leads to comparatively less fixation.

CHAPTER V

PHYSICAL MODELS IN MORE REALISTIC DESIGN SITUATIONS – QUALITATIVE STUDY ON DESIGN PROJECTS

The controlled experiments presented in the previous chapters provide very valuable insights about the cognitive effects of physical models in engineering idea generation. They show that physical models supplement designers' erroneous mental models and lead them to more functional ideas. They also show that as the cost associated with the building process increases, the chances of design fixation also increase. The study presented in this chapter replicates these results in more realistic design situations. This study also investigates the Mental Models Hypothesis and the Fixation Hypothesis from Chapter III; but in more realistic design cases. Data from graduate design teams solving industry-sponsored design projects and case studies of award-winning products are used for the present study.

Hypotheses

Consistent with Chapter III, the following hypotheses are investigated in this study:

Mental Models Hypothesis: Physical models supplement designers' mental models.

Fixation Hypothesis: The Sunk Cost Effect during the building of physical models leads to design fixation. Design fixation is not inherent to physical representations but instead due to the Sunk Cost Effect.

Method

To evaluate the hypotheses in real world design situations, a qualitative approach is used. In realistic settings, the effects of physical models on designers' mental models and design fixation do not have independent effects on the outcome. In controlled laboratory settings, these effects can be separated using relevant conditions. However, in a qualitative setting, it is difficult to find metrics which can capture these effects independently. Hence two metrics are developed to infer these effects and the hypotheses are evaluated by measuring these metrics simultaneously. The two metrics used in this study are: (1) Fraction of changes during the modelling stage which result in improvements to the ideas (2) Frequency of changes to the features that are being tested. Table 9 provides the relation between the outcomes of these metrics and the hypotheses being investigated in this study. For example, consider case 1 in the table. In this case, if the design fixation is present and the designers' mental models are supplemented, the changes made to the ideas cause improvement in a significantly higher number of cases and the tested features change more frequently than those not tested. Conversely, results in case 1 indicate that physical models supplement designers' mental models and lead to design fixation. Similarly, if most changes result in improvements and the frequencies of both tested and not tested changes are similar, design fixation is absent and designers' mental models are supplemented. Only these two cases are of interest in light of the presented hypotheses and the results from the studies described in the previous chapters.

Cases 2 and 4 are indistinguishable using the current metrics, but they are not of interest.

Table 9: Interpretation of the various metrics used for the analysis of data

Case	**Design Fixation is present**	**Mental Models are supplemented**	**Did Changes Improve the Idea?**	**Comparison of Frequency of changes in features evaluated by the physical model**
1	Yes	Yes	Yes	Tested > Not Tested
2	Yes	No	No	Tested = Not Tested
3	No	Yes	Yes	Tested = Not Tested
4	No	No	No	Tested = Not Tested

There are two data sources used for this study: data from industry-sponsored projects and data reported in books about the development of award winning novel products. More details about these data sources and the procedure followed are given in the sections below.

Industry-Sponsored Projects Data

These data are collected from graduate design teams generating concepts for their design projects as a part of the "Advanced Product Design" course at Texas A&M University. This course covers the basic product design procedure with a focus on creativity. The students in this course are divided into various teams of 1 to 4 people. Each team is assigned a project. Majority of the projects are sponsored by industry. The details of the problems are not reported in this chapter, due to confidentiality. The teams do all parts of preliminary design including customer needs collection, creating technical specifications, functional modelling, concept generation and down-selection of concepts. Towards the end of the semester, the design teams are required to build proof-of-concept models for their concepts. They are allowed to build either physical or virtual models for their proof-of-concepts. The teams are required to submit a final report to the instructor which covers all the details about their designs. The data are collected from the teams using specially designed templates and their final reports. The teams are asked to report all the changes they make to their ideas in the proof-of-concept stage. Majority of the proof-of-concept models are physical models and the rest are a few virtual models done in SolidWorks 3-D modelling package.

The data reported in this chapter are collected over two semesters. For the first semester, the data is collected mainly from the reports of the teams. Specially designed templates are provided to each team which requires reporting of the features they measure, the associated physical principles, the methods they use for testing, any changes they make during the building and alternative changes they can think of, if any. The templates are designed to enable direct reporting of the changes during the building process by the students. These teams failed to fill the templates provided to them correctly. Hence most of the data are collected directly from the final reports of the teams. These templates are revised based on the feedback from the first semester and reused in the second semester. The revised templates also collect the same data as the first one, but the questions are re-arranged to make them clearer to students. The templates filled by the teams show that there is a difference in the quality of the data obtained from both templates. For the teams from the second semester, the data from the templates are used. However, for teams that fail to include any relevant data in the templates, the data are collected from their final reports. A portion of the second template version filled with a change during the development of OJex Manual Citrus Juicer (This is an award-winning product as explained in the next paragraph) is shown in Figure 31. Since the quality of template used varies across the two semesters, it can bias the data. However, any missing data is added from the final reports of the teams to bridge this gap. There are a total of five design teams in the first semester and seven in the second. The data from two teams in the second semester are not considered for analysis because they do not use any physical or virtual modeling.

Proof-of-concept name	**Purpose of the proof-of-concept**	**Features tested**	**Test used**	**Was it scaled?**	**Did the test give satisfactory results?**	**Any modifications made to the idea?**	**If yes, what?**	**Did the change improve the idea?**	**Limitations observed, if any**
Bread-board model	Check the operation of the mechanism	Operation of mechanism	Operation of the full scale wooden model	No	Yes	Yes	Mechanism modified	Yes	None

Figure 31: Proof-of-concept template provided to graduate design teams

Award-winning Products Data

The case studies of award-winning products are used as a data source [11, 103] . Ten products are selected for analysis. Most of these products are honoured by the Industrial Design Excellence (IDEA) award by Business Week magazine. The criteria for the selection of the products are that the developers use physical or virtual modelling as a tool for their design and they report the changes they make during the modelling stage. Figure 32 shows the various physical modelling stages of OJex Manual Citrus Juicer, which is one of the ten products being considered. The other products that we use are: BMW StreetCarver, Cachet Chair, Clip ‘n’ Stay, Watercone, Watergate, Bottle Stopper/Opener, Scorpio 270, Overflowing bath and Snowboard boot (Figure 33).

Figure 32: Physical models used by the developers for OJex Manual Citrus Juicer

OXO Bottle Stopper/Opener

Scorpio 270

Watercone

BMW StreetCarver

Water Gate

Over Flowing Bath

Ekco Clip 'n Stay

OrangeX Juicer

Cachet Chair

Burton Ion Snowboard Boot

Figure 33: Various award-winning products used for the qualitative analysis

Procedure

A qualitative approach is used to code the data and the obtained metrics are analyzed using statistical methods to evaluate the hypotheses. The qualitative coding process used in this study is based on previous studies in design [104, 105] and qualitative procedure used in Psychology [106]. In this study, the author determines the coding categories required to evaluate the hypotheses, based on the metrics presented in Table 9. Table 10 shows the categories that are used for this study. Then the author goes through all the available data including the project reports, templates and case studies and notes down all the information related to the changes during the physical or virtual modelling process. Then these data are organized into the various pre-determined categories. The data in each category are counted to form the metrics. These metrics are analyzed using a chi-square test.

Table 10: Coding categories used for the data

Metrics	**Categories Identified**
Changes made during physical modeling	Improves the idea
	Does not improve the idea
	Designer realizes the idea is infeasible
Feature that change during the physical modeling	Features are tested intentionally
	Features are tested unintentionally
	Features are not tested

If designers deliberately test a feature with the intention of verifying or improving it, it is considered as intentional testing. At the same time, in many cases, tests using physical models for few selected features provide information regarding the possible or required improvements in the other associated features. The designers make changes to these features. Such tests are termed as unintentional tests.

Among the categories shown in Table 10, cases where designers realize the infeasibility of the idea during physical modeling are excluded from analysis. In such cases, designers do not attempt to make changes and instead interpret that the ideas cannot be made functional. Four such cases are identified in the industry-sponsored projects data. These cases are difficult to interpret with the present metrics and are left for future work.

To illustrate the procedure, consider the example of a design change reported during the development of bread-board model of OJex Manual Citrus Juicer shown in Figure 32. The test reported is designed to evaluate the mechanism operation (using the two-dimensional model for motion studies) and it results in a change which improves the idea, as reported by the developers. This change is considered as a change resulting from an intentional test and one that improves the idea. In a similar manner, other changes in the development of this product are also considered. To ensure reliability of this procedure, an independent judge repeated the coding procedure. This second judge is a graduate student in design and is given about 90% of the total data. An inter-rater agreement of 0.98 (Pearson's correlation) is obtained, which is high, showing that the procedure is reliable [92].

Results and Discussions

The qualitatively coded data are counted to convert them into quantitative measures and then analyzed to address the hypotheses. The results show that most of the changes made while building physical models lead to the improvements in the ideas and the features tested change more frequently than those not tested. In reference to Table 9, this supports both of the hypotheses presented. It demonstrates that physical models support designers' mental models, meanwhile leading to fixation. The full results are detailed below.

It is likely that there is a reporting bias in the books and probably a hindsight bias also. The books likely report successful changes quite frequently, but very rarely report unsuccessful ones. Hindsight bias probably also causes the award winning product cases to present what they learned during testing as intentional instead of accidental. Since the initial industry-sponsored data was captured before testing, the unintentional tests can be identified.

As shown in Figure 34, it is observed that majority of the changes that designers make after making physical models of their ideas result in an improvement in the respective idea. In case of industry-sponsored projects, very small fraction of changes do not result in an improvement. In case of award-winning products, this fraction is further less, but this can be due to the reporting bias. The states of the idea before and after each change are carefully considered to determine whether the change results in an improvement or not. A chi-square test demonstrates that in significantly higher number of cases the changes not including those resulting from unintentional ones result in improvements in ideas (χ^2=3.60, p=0.06). This significance goes up as the changes from unintentional tests are included (χ^2=13.50, $p < 0.001$).

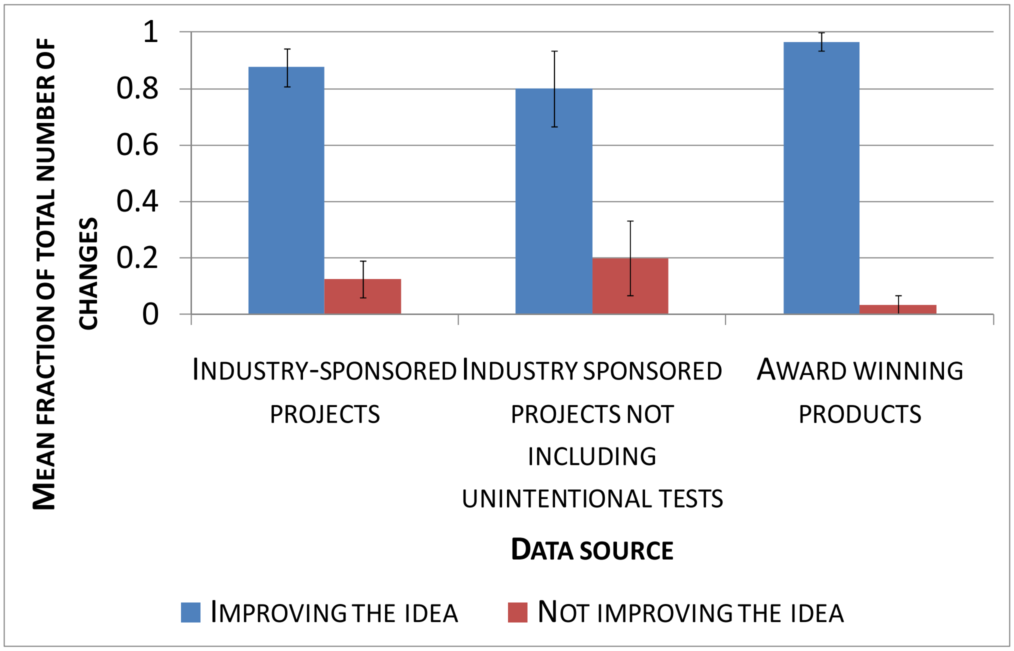


Figure 34: In most cases, the changes during physical modeling result in an improvement of the idea. The error bars are +/- one standard error

The data show that in majority of the cases, the features tested change very frequently and the features not tested remain the same, as depicted by Figure 35. A chi-square test shows that this is statistically significant without including unintentional tests (χ^2=10.89, p<0.001) and with including the unintentional tests also (χ^2=20.57, p<0.001). Again, the award-winning product cases may be biased since they report even unexpected changes as results of intentional tests. However, Figure 35is used to show that in award-winning product design cases also this trend is true.

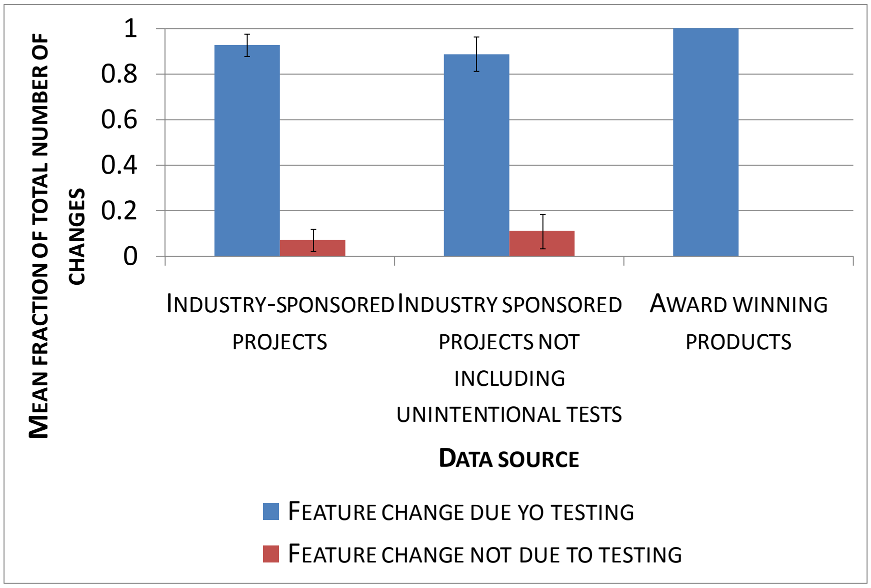


Figure 35: Majority of the changes during physical modeling result from tests. The error bars are +/- one standard error

Comparing the above mentioned results with the cases presented in Table 9, the data show trends similar to Case 1. In significantly higher number of cases the changes during physical modeling result in improvements in the ideas. The frequency of changes resulting from tests is significantly higher than that of those not resulting from tests. According to Case 1, these results indicate that physical models supplement designers' mental models and also cause fixation. The data agree with the hypotheses.

Intentional and Unintentional Testing of Features

The data demonstrates that many of the feature changes result from unintentional testing. Figure 36 shows the fraction of the two kinds of tests observed in the industry-sponsored project data. The award-winning product data report all the tests as intentional, likely due to hindsight bias. Very importantly and unlike currently available virtual models, physical models are capable of providing useful insights about the possible improvements in their designs even when the features are not intentionally tested. This result also highlights the importance of encouraging building of physical models as a part of the engineering design process.

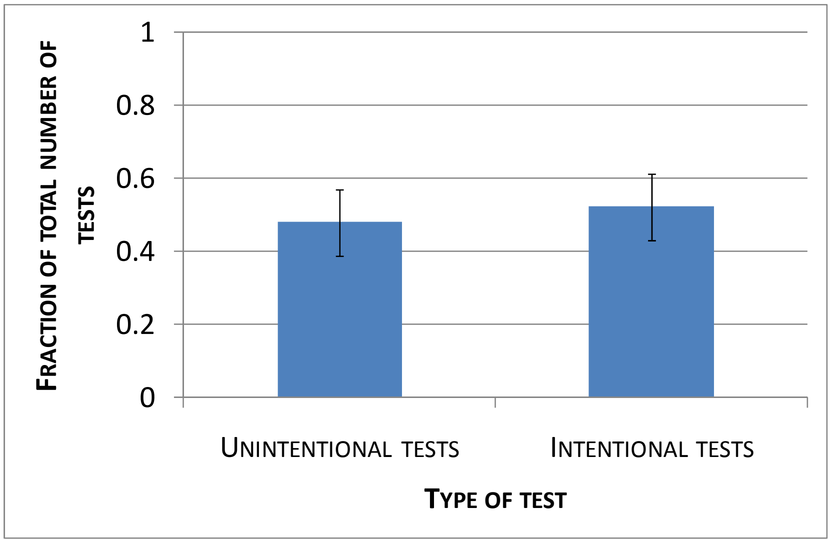


Figure 36: Building physical models leads to both intentional and unintentional tests. The error bars are +/- one standard error.

Triangulation with the Controlled Study

As described above, the data show that building physical models of ideas during the design process leads to more changes, which results in idea improvements. The data also show that tested features change much more frequently than the features which are not tested. Comparing these results with the theory presented in Table 9, it can be interpreted that physical models supplement designers' erroneous mental models and also cause design fixation. This supports both of hypotheses presented in this study.

To clarify the role of physical models in design cognition, these results can be triangulated with those from controlled studies described in the previous chapters (Table 11). The results from the controlled studies show that physical models supplement designers' erroneous mental models. This result is replicated in this qualitative study too. At the same time, the controlled studies fail to show the fixation caused by the building process. However, the data from the current study shows that designers fixate to their initial ideas. The controlled studies use a very simple design problem and we attribute the absence of fixation in the controlled studies to Sunk Cost Effect [41, 47], as explained in Chapter IV. Once significant amount of money, effort or time is invested in a course of action, it is unlikely that the designer will choose a completely new course. For both the current and prior studies, Sunk Cost Effect explains the findings. In the previous controlled studies, the sunk cost is low as the design problem is very simple, hence designers do not fixate. In the current study, all the design problems are complicated and have comparatively larger sunk costs. Hence, the building process leads to fixation in these cases. This result is also consistent with those from the Sunk Cost Experiment explained in Chapter IV.

Table 11: Triangulation of controlled and qualitative studies

	Controlled experiments (Chapters III and IV)	**Qualitative study**
Mental models hypothesis	Supplemented	Supplemented
Fixation hypothesis	As cost increases, fixation occurs	As cost increases, fixation occurs

Conclusions

The evidence obtained from this study provides strong support to the results from the previous controlled studies. The data show while building physical models, designers often make changes in their ideas. These changes result in the improvement of their ideas in significantly higher number of cases. In significantly higher number of cases, these changes are resulting from intentional or unintentional tests. These results demonstrate that physical models supplement designers' erroneous mental models and help them to improve their final designs. Due to erroneous mental models, designers tend to generate infeasible solutions during idea generation, whereas the use of physical models helps them to come up with more feasible solutions. At the same time, they cause designers to fixate to their initial solutions. This restricts their solution space, thereby restricting the novelty and variety of their ideas. The difference in results of this study with the prior controlled study provides a good argument for the presence of the Sunk Cost Effect in design problem solving with physical representations. Unlike the paperclip design problem, the design problems involved in these cases are complicated and involved higher cost building. Hence in these cases, building physical models may lead designers to fixation.

CHAPTER VI

ROLE OF PHYSICAL MODELS IN MITIGATING DESIGN FIXATION – THE STUNT CAR EXPERIMENT

The studies discussed so far in this thesis have demonstrated that design fixation is not inherent with physical models. They lead designers to ideas with higher functionality, by supplementing their erroneous mental models. Many times, designers fixate to undesirable features from the examples in their environment that affects the functionality of the designs they generate. As physical models have the potential of revealing flaws of generated designs, they may act as tools for mitigation of fixation to undesirable example features. Based on this argument, the studies described in this chapter investigate the role of physical models in the mitigation of design fixation.

Hypotheses

Based on the arguments presented above and the literature discussed in Chapter II, the following hypotheses are investigated in this chapter:

Fixation Hypothesis: Novice designers generating ideas for a design problem with the help of an example solution will fixate to the features of the example solution. This fixation can be reduced by providing warnings to the designers about the undesirable features.

Mitigation of Fixation Hypothesis: If novice designers are allowed to build and test physical models of their ideas, they will identify the flaws in their designs caused by the fixation to negative features and rectify them.

To investigate these hypotheses, two experiments were conducted. The first one was a pilot study and possessed certain limitations. The second study eliminated these limitations and was conducted with a larger sample size. The following sections describe the details of these studies.

Experiment 1 – Pilot Study

This pilot study was conducted with freshmen engineering students as a part of their regular class project. The students were asked to solve a design problem and build physical models of their solutions. More specifically, the participants designed and built stunt cars satisfying functional and performance requirements. Participants completed the project in groups containing two or three other participants. Each of these teams was randomly divided into one of two groups. Both the groups received the same problems statement. Based upon their group, the team received a specific example solution. One condition received a flawed example solution which contained certain flawed features, while the second received an effective one. In an effort to understand the level of fixation, to the provided example, photographs of the physical models were studied. The method followed is described in greater detail in the subsequent sections.

Participants

63 engineering freshmen attending a “Fundamentals of Engineering” course at Texas A&M University participated in the study. These students were divided into 15 teams with 3-5 students each. They completed this study as part of their regular class project schedule. The teams were expected to design, build and test stunt cars as a part of the project. They were instructed to present a working prototype at the end of the project. The physical models of their initial and final designs were photographed and these photographs were used for analysis in this study. As compensation for their participation in the study, the students were provided extra credit in the class. The project was a requirement of the class.

Design Problem & Materials

The teams were asked to design and fabricate a stunt vehicle that could be launched from a ramp of known dimensions as a projectile with a known velocity. Following its release from the top of the ramp, the vehicle was supposed to gain a launch speed sufficient to cover a horizontal distance of 100cm. As an added constraint, the vehicle had to remain in one piece after the landing. Figure 1 shows the diagram provided to students in order to clarify these instructions.

The ramp was available to the students to make necessary measurements. Furthermore, participants were provided with a photo-gate for measuring the speed of the vehicle as it exited the ramp. The billboards were placed at distances $D_1 = 50$ cm and

$D_2 = 70$ cm as shown in Figure 37. To build the physical models, the teams were provided with LEGO kits. The kit contained a variety of parts that might be or might not be helpful in the building of cars.

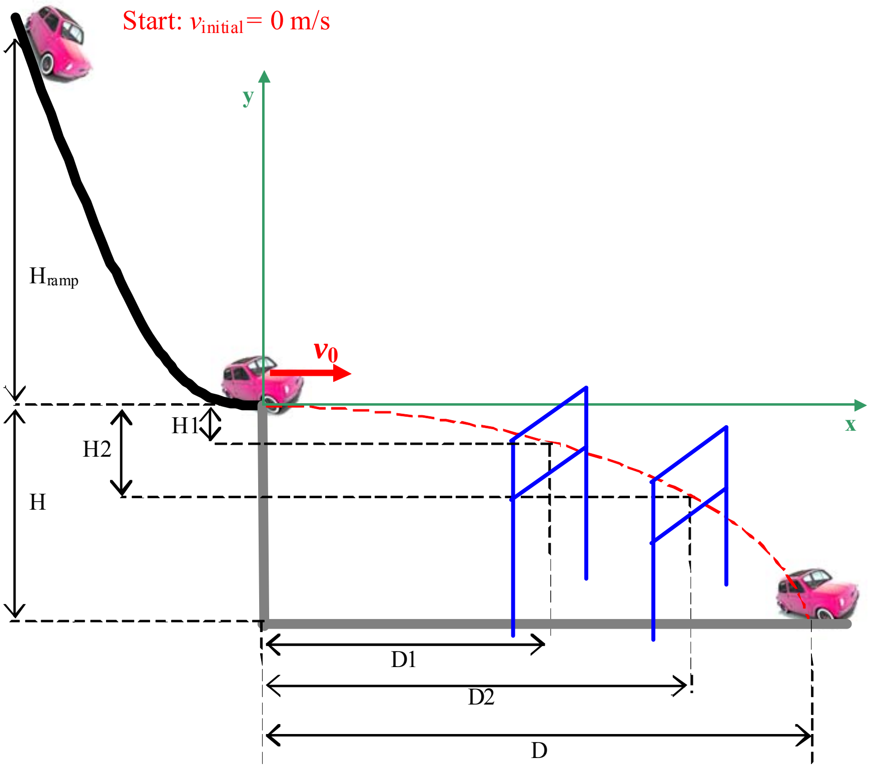


Figure 37: The sketch provided for participants along with instructions

Experimental Groups

Ten teams received a design problem which included an example solution with a few flawed features. These features would restrict the functionality of their cars if they implemented them. Figure 38 shows the flawed example they received. For the rest of the chapter, this example is referred to as the “flawed example” and the teams who received this example are referred to as the “Flawed Example Group.” This car was made of heavy bricks, leading to an extremely bulky design. Additionally, this type of design could not survive a fall from waist height, failing the crash test. With a pair of bulky tires that restricted its movement, the design often came off the ramps. As evident from Figure 38, this design also used different sizes of tires at the front and back, causing an imbalance in the center of gravity, because the front tires were considerably heavier that the back ones. The students were not informed of these flaws in the flawed example design.

Remaining five teams received an example without these flawed features. Figure 39 shows the example provided to this group. This example primarily consists of LEGO beams, a very sturdy design. Since the design uses the same tires in the front and back, its overall design is compact and lightweight with no center of gravity imbalance. Throughout the chapter, this example is referred to as the “effective example” and the teams who received this example are referred to as the “Effective Example Group.” Also, in this group, the students were not informed of the “effectiveness.” of the example.

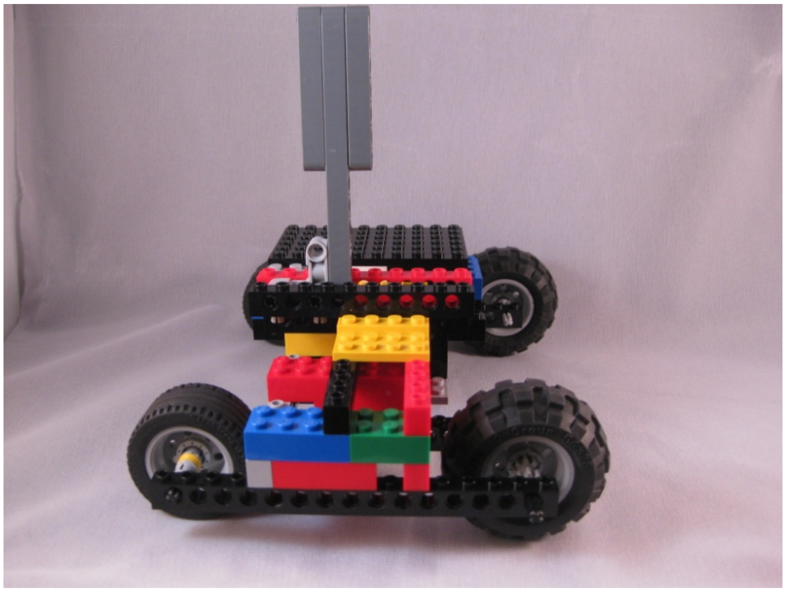


Figure 38: The example provided to flawed example group

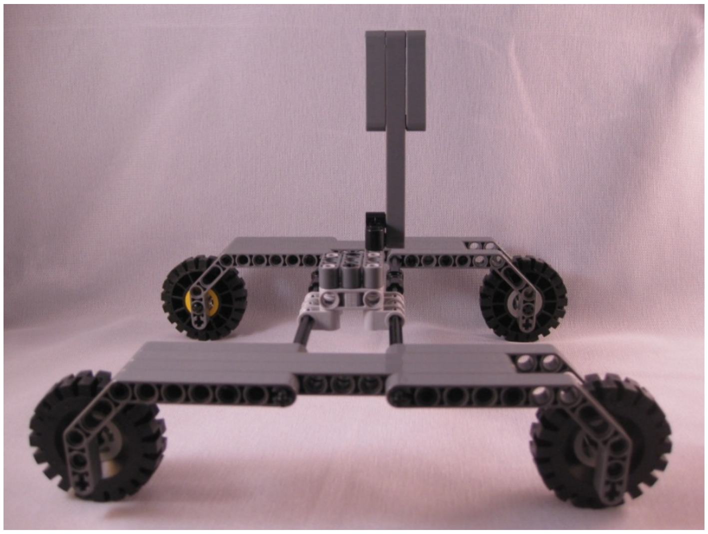


Figure 39: Example provided to effective example group

Procedure

The study took place during two regular class periods, 1 hour 50 minutes each. The second period (referred as class 2 further) was separated by one week from the first one (referred as class 1 further). In class 1, the students received a lecture concerning projectile motion. Next, the teams received a technical memo (See Appendix D) containing the details of the design challenge and an example solution. As specified in the technical memo, each group was supposed to build at least two different cars out of LEGOs. In class 1, they developed their initial designs and tested them on ramp. Before testing on the ramp, the participants were instructed to conduct a drop test. The drop test entailed dropping their cars from waist height to test their car's durability and ability to survive a sudden crash. Pictures of the cars were taken before the drop test, but the students were not informed of the exact purpose of the pictures. They were told that it is intended to study the evolution of their designs over time. Considering the requirements mentioned in the technical memo, the teams were asked to modify their designs until they created two designs that satisfied the specifications. The ramp and LEGO kits were accessible to students for modifying and testing their designs during the one week gap between the two class periods. At the beginning of class 2, the teams were asked to demonstrate their two cars on the ramp. Once again, pictures were taken before these demonstrations. The pictures were captured from several angles to obtain a sufficiently detailed picture of the cars. If necessary, these detailed pictures allowed the reconstruction of a car.

Experiment 1 - Metrics for Evaluation

This study investigates the fixation of novice designers to undesired features of the presented flawed example and how it changes as participants build their ideas. The flawed example contains three features that restrict its functionality: the use of LEGO blocks as construction units which makes the design bulky, the use of bulky tires which makes the movement of the car difficult on the ramp and the use of different tires which causes a center of gravity imbalance in the design. Three metrics representing the frequency of appearance of these undesirable features in participants' designs [12, 13] are used for this study: Relative percentage of blocks used by the participants in their designs, percentage of cars using bulky tires and percentage of cars using differently sized tires, causing an imbalance in their center of gravity.

Relative percentage of blocks is calculated as the ratio of the total number of LEGO blocks used in each design to the total number of blocks and beams used in the design. Students use three different kinds of parts in their designs: LEGO blocks, LEGO beams and other parts including connectors, axles, tires and decorative items. The relative percentage of blocks is used, as the larger number of other parts in many designs makes the ratio of number of blocks to total number of parts small and any difference across the conditions insignificant.

Among all the designs, the number of cars using bulky tires is counted and the ratio of this number to the total number of designs generated by the group is considered as the percentage of cars using bulky tires for that group. The percentage of cars using different size tires is calculated in a similar manner. All these three metrics are calculated separately for designs generated in the two class periods (class 1 and class 2). Class 1 designs represent the initial designs generated by the teams, whereas class 2 designs are their final designs. The teams build and test all their ideas between these two stages of the designs and hence the variation of these metrics across the two classes is due to the building and testing process.

It is expected that the teams who receive flawed example fixate to the flawed features and hence their designs contain a higher percentage of these features. However, as they build and test their design, they realize the issues in their designs caused by these features and rectify them, leading to a lower percentage of occurrence of these features in their final designs. As a result, both the groups generate final designs that contain the same lower frequency of occurrence of the flawed features.

Experiment 1 – Results

This section summarizes the results obtained for the three metrics mentioned in the previous section. Each car design is analyzed separately to calculate these metrics. A detailed discussion of the results follows.

Flawed Design Feature 1 – Use of Blocks

Figure 40 shows the variation of relative frequency of blocks across the experimental groups and the two class periods. It is observed that teams who receive the flawed example use LEGO blocks as the building units for majority of their designs compared to those who receive the effective example. A t-test shows that this difference is statistically significant (t = -1.49, p = 0.07). As shown by Figure 40, both groups produce the same lower relative percentage of blocks in their final designs in class 2. For the Flawed Example Group, a t-test shows that the final designs contain significantly lower relative percentage of blocks compared to the initial ones (t = -1.57, p = 0.06). The relative percentage of blocks remains constant for the Effective Example Group across initial and final designs. This shows that as the participants in Flawed Example Group build and test their cars, they notice the problems caused by the use of blocks and rectify those by reducing the number of blocks in their further designs.

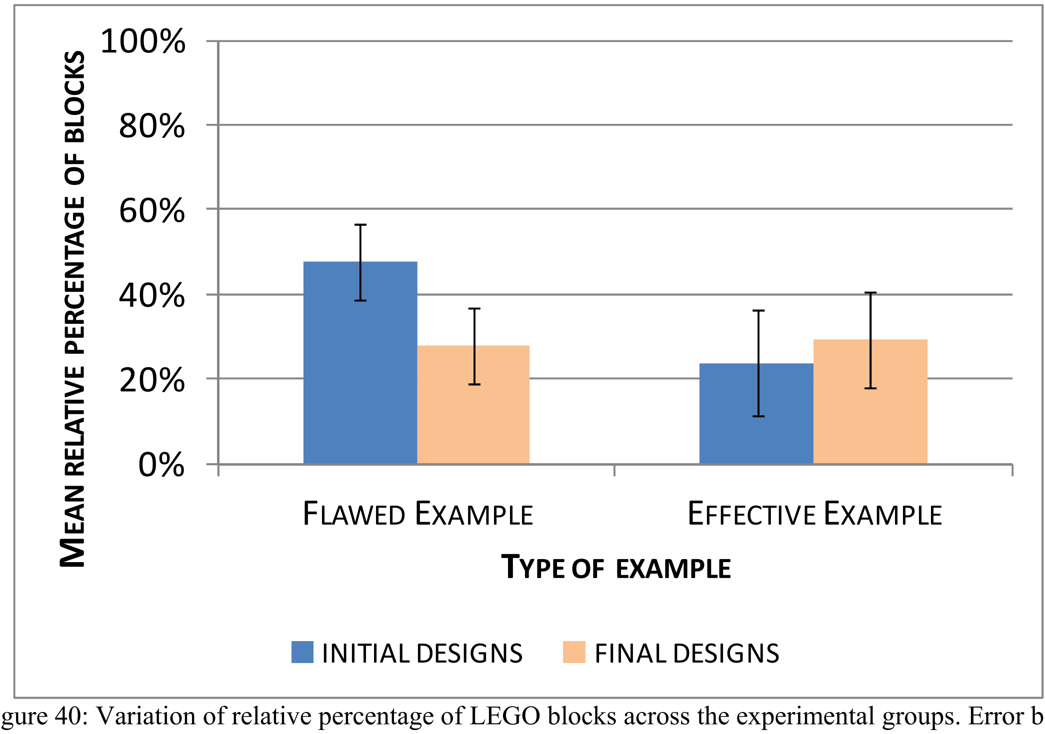


Figure 40: Variation of relative percentage of LEGO blocks across the experimental groups. Error bars show (±) 1 standard error

Flawed Design Feature 2 – Use of Bulky Tires

Figure 41 shows the variation of percentage of designs using bulky tires across the two experimental groups. It can be observed that the teams who receive the flawed example get fixated to this flawed design feature and replicate that feature in their designs more frequently than the Effective Example Group, which is consistent with the Fixation Hypothesis. A χ^2-test shows that the use of bulky tires depends on the type of example provided to the groups ($\chi^2 = 4.62$, $p = 0.03$). It is also observed that as teams build and test their cars, they remove bulky tires in their designs causing a lower percentage of designs with bulky tires in their final designs. This result provides strong support to the Mitigation of Fixation Hypothesis.

Flawed Design Feature 3 – Use of Different Size Tires

Figure 42 shows the variation of percentage of designs using different size tires that causes an imbalance in center of gravity. It can be observed that the Flawed Example Group produces approximately same percentage of designs with different size tires as the Effective Example Group. Accordingly, a χ^2-test shows that the use of different size tires by the design teams is independent of the type of example provided to them. The Flawed Example Group shows a slight decrease in the percentage of designs with different size tires as they build and test their designs (initial designs to final designs). For the Effective Example Group, this percentage remains constant across initial and final designs. These results do not provide support to the hypotheses.

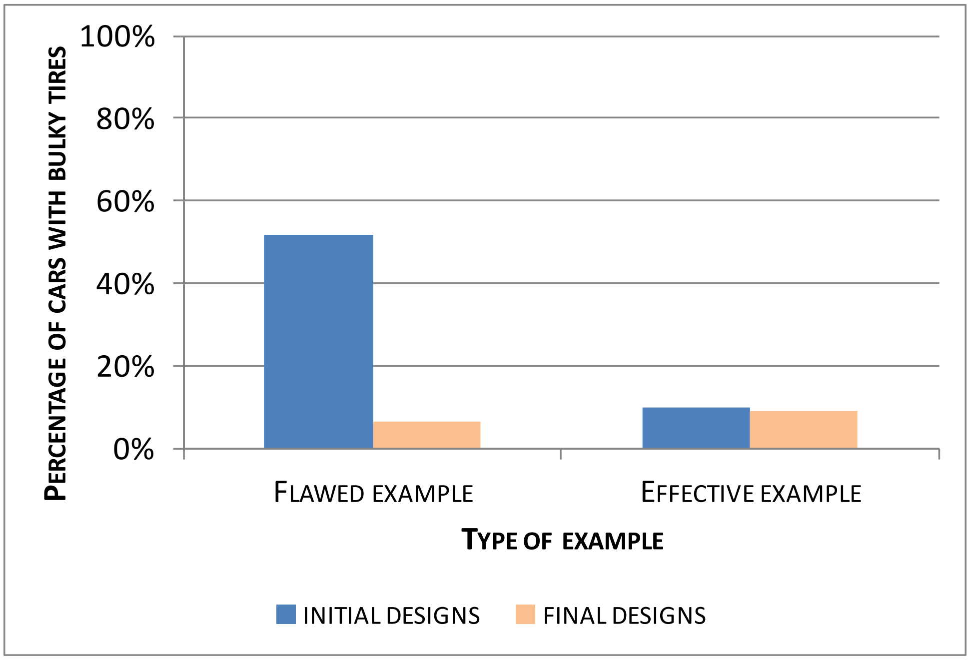


Figure 41: Percentages of cars using bulky tires in the experimental groups

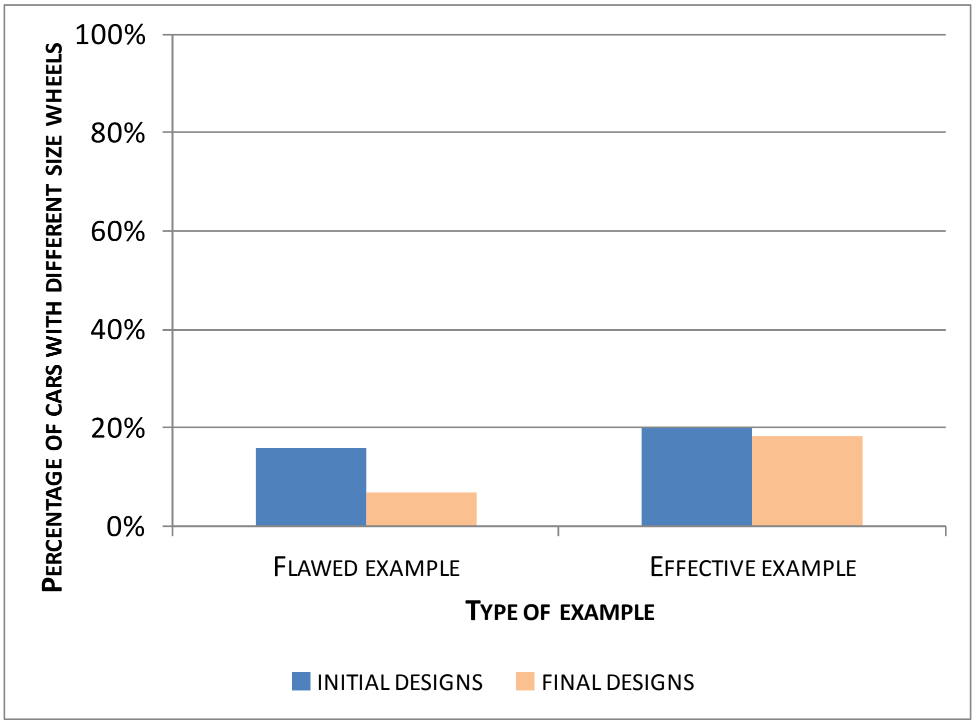


Figure 42: Percentages of cars using different size tires across the experimental groups

Experiment 1 - Discussion

Fixation Hypothesis – Fixation to the Features of the Flawed Example

The obtained results provide strong support for the Fixation Hypothesis. According to this hypothesis, students who receive flawed example with certain features restricting its functionality tend to reproduce those features in their designs. The frequencies of occurrences of two out of three flawed design features in the Flawed Example Group are significantly more than the Effective Example Group. This shows that student teams who receive the flawed example fixate to the features of that example, thereby restricting the functionality of their designs. This trend is not observed in case of the use of different size tires that causes a center of gravity imbalance. The frequency of occurrence of this flawed design feature remains constant across the two groups. This could be due to the potential cross contamination across the groups. Although the two groups receive different examples, they build and test their designs in the same class room and they can see other groups' designs. This can influence the teams and can cause a bias in their designs. Another possible explanation is the student's awareness of the disadvantages of unsymmetrical designs.

Mitigation of Fixation Hypothesis – Physical Models Mitigate Fixation to Negative Features

The results obtained also provide strong support to the Mitigation of Fixation Hypothesis. According to this hypothesis, the student teams who are fixated to the features of the flawed example need to identify the issues due to this fixation as they build and test the physical models and eventually get rid of this fixation. If this hypothesis is true, the final designs of the Flawed Example Group are expected to contain lower percentage of flawed design features compared to their initial designs. This trend is observed for all the flawed design features associated with the flawed example. This shows that students identify the flaws and correct them as they build and test the physical models of their designs, in the process mitigating their fixation.

Limitations of Experiment 1

Though the results from Experiment 1 provide insights supporting the presented hypotheses, it possesses a few limitations. First, the sample sizes across the groups are unbalanced (10 in the Flawed Example Group and 5 in Effective Example Group), which may lead to a bias in the statistical analysis. This is imbalance is caused by the unavailability of participants. These data also suffer from cross-contamination across the groups as mentioned in the previous paragraph. Both the groups work on their project inside the same class room. Though the groups receive separate examples, they are able to see the examples and designs of the other group. This can cause fixation to the other group's designs and hence can cause significant bias in the results. Experiment 2 eliminates these concerns with a more balanced distribution of subjects and isolation of the groups from each other. The further sections in this chapter provide details of Experiment 2.

Experiment 2 – The Stunt Car Experiment

This experiment was a modified version of Experiment 1 with similar experiment setup and with a larger sample size. This experiment differed from Experiment 1 in a few aspects. A new experimental group called "Flawed Example with Warning Group" was added to this experiment. This new group received the same flawed example as in Experiment 1 along with warnings about the use of the flawed design features. This condition intended to investigate any potential effects of warnings about flawed features in mitigating fixation to those features. Three different sections of the same class were used for this experiment. Each section was given the same design problem but a different example solution to the problem: the effective example, the flawed example, and the flawed example with warnings about the flawed features. All these sections had approximately the same number of students and thus the sample sizes were more balanced across the groups.

Participants

A total of 281 engineering freshmen attending a "Fundamentals of Engineering" course at Texas A&M University participated in this study. The group who received the effective example had 89 participating students, divided into 22 teams with 3-5 students each. 96 students divided to 24 teams received the flawed example, and another group of 96 students in 24 teams received the flawed example along with the warnings about the flawed features. The students completed this study as a part of their regular class project. Similar to Experiment 1, photographs of the physical models were taken before each testing to analyze the fixation to the flawed features. The students received extra credit in the class as a compensation for their participation.

Design Problem and Materials

The design task remained the same as in Experiment 1. All the groups received the same technical memo along with the example as determined by their group.

Experimental Groups

There were three freshman engineering classes used in this experiment, with one type of example per class. The first class received the flawed example (Figure 38). This group is referred to as "Flawed Example Group" further in this chapter. The second class who received the effective example (Figure 39) is referred to as "Effective Example Group" further.

The third class received the same flawed example as in Figure 38, but was also presented with warnings about the flawed features in the design. The exact wording included in the example was as follows: "Note that this is a poor example as it uses bulky bricks and heavy tires. It also uses different tire sizes in the front and back causing an imbalance." This example is referred to as the "flawed example with warning" and the teams with this example are referred to as the "Flawed Example with Warning Group" further in this paper.

Procedure

The procedure for this experiment was similar to that of Experiment 1. This study also took place during two regular class periods of 1 hour 50 minutes each. The two periods were one week apart. In the first class period, a lecture about projectile motion was provided to students by their instructor. Then, the teams were provided with a technical memo containing the details of the design challenge and the example solution. Each group was asked to build two cars out of LEGOs. In the first class period, the students made their initial designs and tested the cars on the ramp provided to them. They were instructed to conduct a drop test before they could test the cars on the ramp. In the drop test, the cars needed to be dropped from waist height and only if the cars were able to survive this test, they were allowed to be tested on the ramp. Pictures of the cars were taken before the drop test each time. The students were not informed about the actual purpose of the pictures, but were told that we intended to study how their designs evolve over time. The teams were asked to modify their designs until they achieved two designs that satisfied all the requirements mentioned in the technical memo. The ramp and LEGO kits were accessible to students for modifying and testing their designs during the one-week gap between the two class periods. At the beginning of the second class period, the teams were asked to demonstrate their two cars on the ramp and pictures were again captured before these demonstrations. The pictures were captured from many different angles to obtain sufficient details of the cars, so that a reconstruction of the cars was possible, if necessary.

Experiment 2 - Metrics for Evaluation

This experiment also used the same three metrics as used by Experiment 1 – the relative percentage of LEGO blocks used, percentage of designs with bulky tires and percentage of designs with different size tires.

According to the Fixation Hypothesis, students who received the flawed example will fixate to the flawed features of the example and replicate those features in their initial designs more often than those who received the effective example. Hence the mean value of all the three metrics need to be higher for the Flawed Example Group compared to the Effective Example one. At the same time, in the Flawed Example with Warning Group, students are given prior warning against the use of those flawed features in their designs, and hence they are expected to fixate less, keeping their metrics equal to that of students who received the effective example. According to Mitigation of Fixation Hypothesis, as students build their LEGO models and test them, they will identify the flaws due to these flawed features and rectify them. This needs to make the mean values of the three metrics equal for their final designs across the three experiment groups.

Experiment 2 – Results

Flawed Design Feature 1 – Use of LEGO Blocks

It is observed that the relative percentage of blocks in the designs produced by the students vary across the experiment groups. Figure 43 shows the mean relative percentage of blocks for the initial and final designs of students in the three experiment groups. It is observed that students who receive the flawed example with or without warning about the flawed features produce a higher mean relative percentage of blocks in their initial designs. However, as they test their physical models and make modifications to them, their final designs contain a lower relative percentage of blocks compared to initial designs. These results provide strong support to the presented hypotheses.

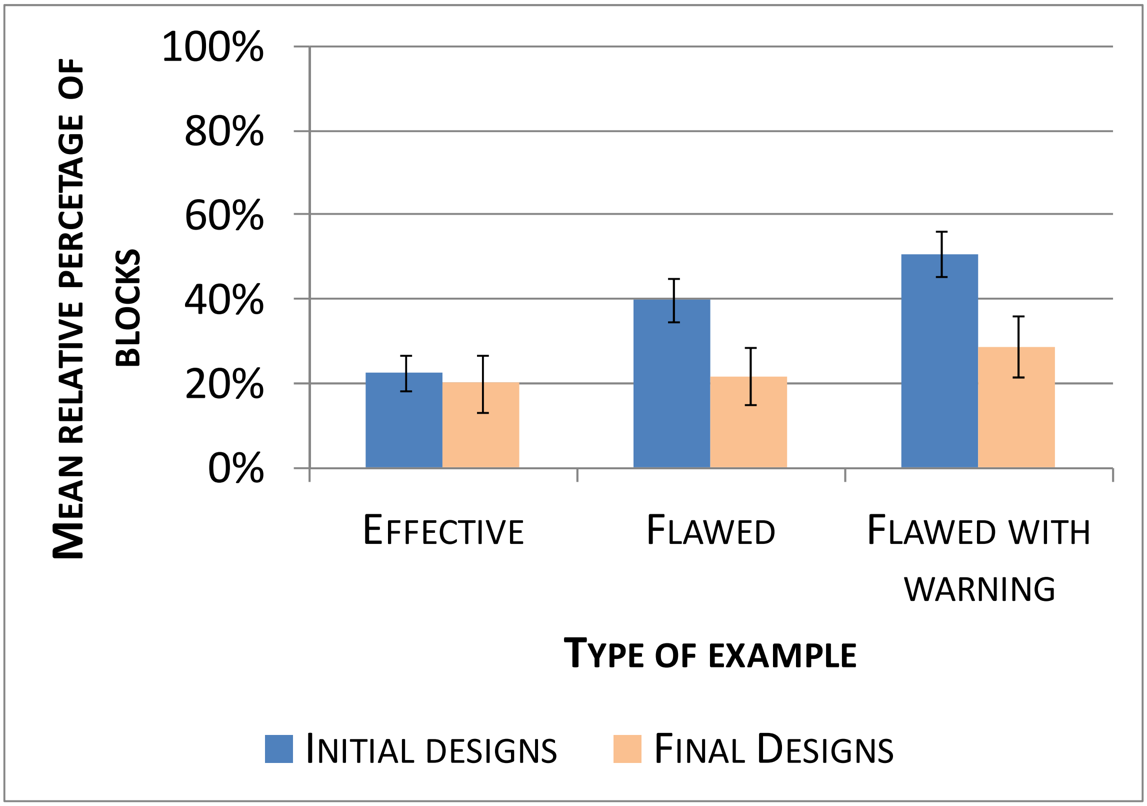


Figure 43: Students who receive flawed example fixate to the use of LEGO blocks in their initial designs and mitigate this fixation to some extent in their final designs. Error bars show (+ or -) 1 standard error.

A non-parametric Kruskal-Wallis test [92, 93], equivalent to one-way ANOVA is employed for the statistical analysis of the data. As these data do not satisfy the normality and homogeneity of variance requirements, so one-way ANOVA results are not reliable. The results from Kruskal-Wallis test shows that there is a significant difference in relative percentage of blocks across the conditions ($\chi^2 = 21.63$, df = 5, p <0.01). It is also interesting to see which pairs of groups are significantly different from each other in relative percentage of blocks. For this purpose, pair-wise a-priori comparisons using Mann-Whitney tests are employed [93]. Table 12 shows the results of these a-priori comparisons.

Table 12: Pair-wise a-priori comparisons for relative percentage of blocks

Pairs compared	p
Fixation to example features (initial designs):	
Effective Example vs Flawed Example	0.09*
Effective Example vs Flawed Example with Warning	<0.01*
Flawed Example vs Flawed Example with Warning	0.09*
Fixation to example features (final designs):	
Effective Example vs Flawed Example	0.89
Effective Example vs Flawed Example with Warning	0.44
Flawed Example vs Flawed Example with Warning	0.45
Mitigation of fixation by physical models:	
Effective Example – initial vs final designs	0.26
Flawed Example – initial vs final designs	0.06*
Flawed Example with Warning – initial vs final designs	0.01*

* denotes statistically significant comparisons at $\alpha = 0.1$

Flawed Design Feature 2 – Use of Bulky Tires

The variation of percentage of bulky tires across the conditions is shown in Figure 44. It can be observed that the Flawed Example Group copies the flawed design feature of use of bulky tires into many of their initial designs, resulting in a higher percentage for that group. The students who receive the warnings along with the flawed example produce a lower percentage of initial ideas with bulky tires compared to those who do not receive warning. However, their percentage is higher than that of Effective Example Group. After revisions of their models, the final designs contain a lower percentage of bulky tires compared to initial designs, except in the case of the Effective Example Group. This result is consistent with the Mitigation of Fixation Hypothesis. A χ^2-test of independence shows that the frequency of use of bulky tires depends on the type of examples given to students ($\chi^2 = 20.73$, $p < 0.001$), showing evidence of fixation to the features of example solutions.

Flawed Design Feature 3 – Use of Different Size Tires

The variation of percentage of designs with different size tires is shown in Figure 45. Students who receive flawed example produce a higher percentage of designs with tires of different sizes compared to the other two groups. However, they show a reduction in the fixation to this flawed design feature in their final designs, showing that in their testing and revisions, they get rid of this fixation, which is consistent with the Mitigation of Fixation Hypothesis. A χ^2-test of independence shows that the frequency of designs with different size wheels depends on the type of example given to students ($\chi^2 = 4.70$, $p = 0.09$). This result supports the Fixation Hypothesis.

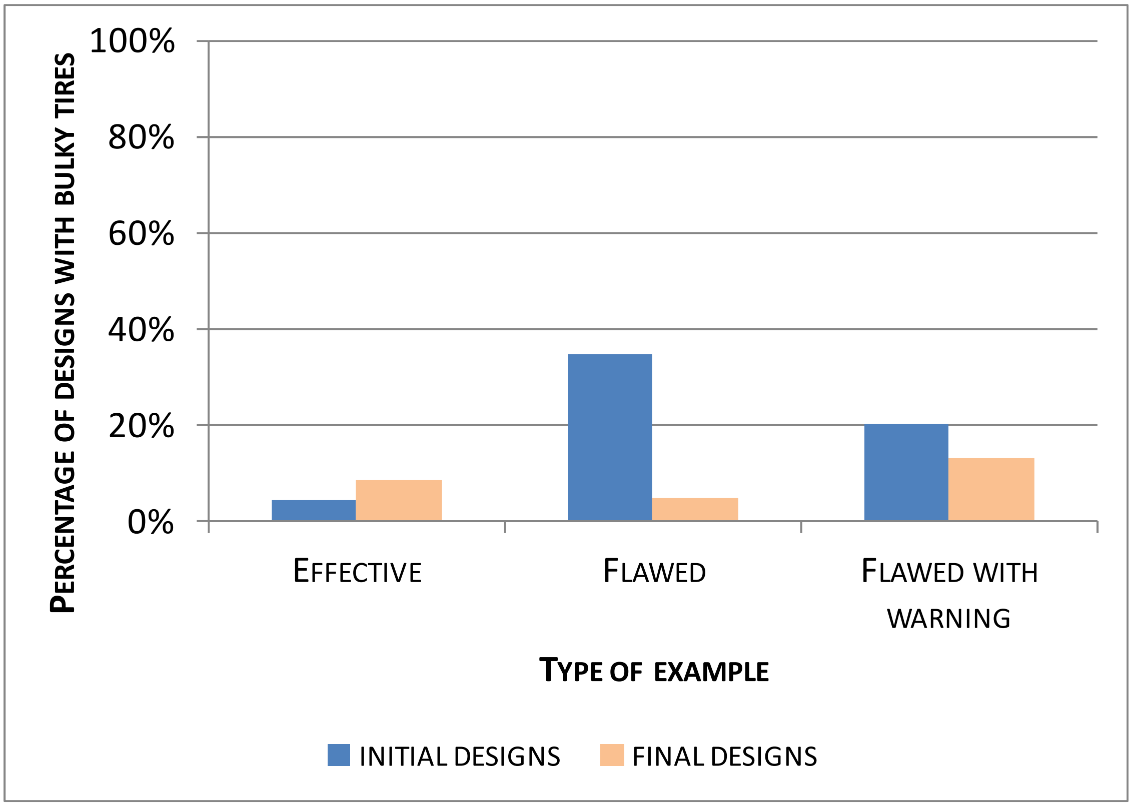


Figure 44: Percentage of ideas with bulky tires across the conditions

Experiment 2 - Discussion

Fixation Hypothesis

In this study, the extent of design fixation to the flawed features in various experimental groups is studied to investigate the Fixation Hypothesis. Ideally, a control group with no example provided to them is needed to infer the extent of design fixation across the groups. However, as the participants are freshmen, instructing them to complete the project without an example is not advisable. Due to this reason, only the flawed design features in the flawed example are considered for the analysis of fixation. These flawed features are absent in the effective example. Thus, the comparison of the Flawed Example Group and the Effective Group can provide insights about design fixation.

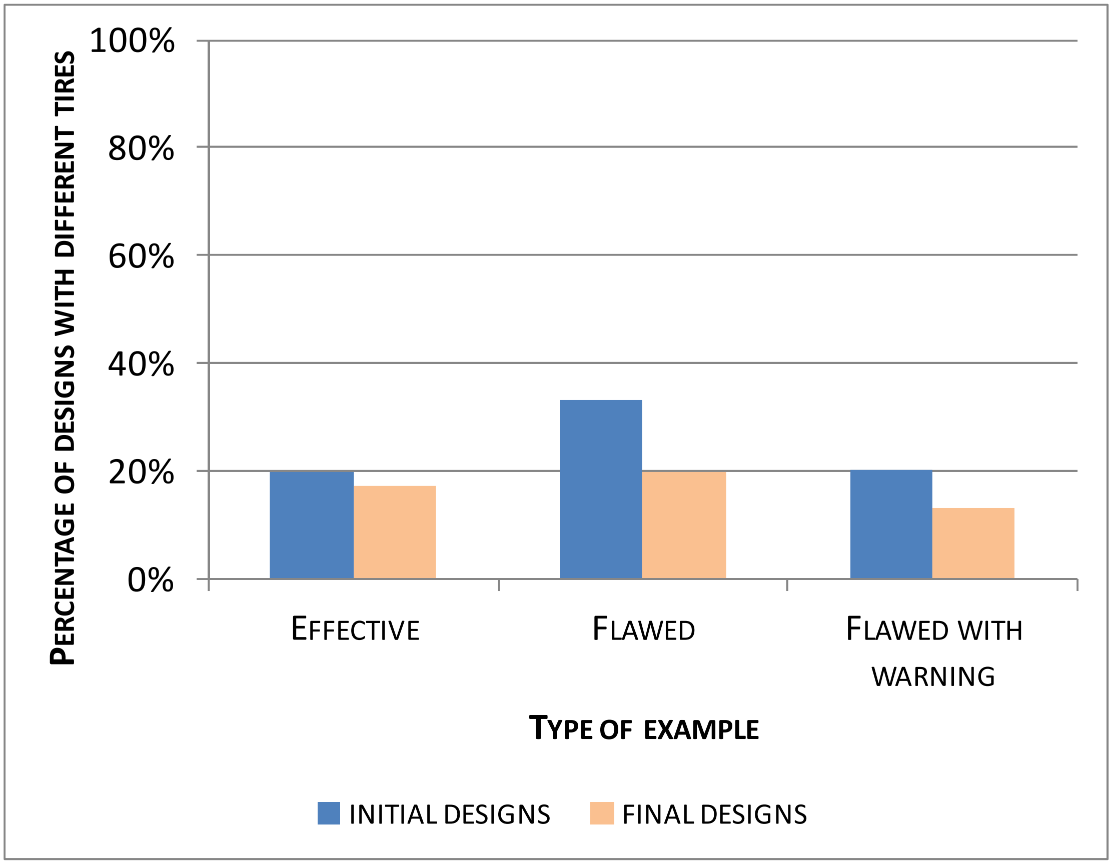


Figure 45: Percentage of ideas with different size tires across the conditions

The obtained results provide strong support to argument that designers fixate to features of example solutions. The Flawed Example Group reproduces the flawed design features in their example in a significantly higher number of cases compared to the

Effective Example Group. However, contrary to expectations, the warnings about the flawed design features do not help students in mitigating their fixation to those features. Hence these warnings are not helpful enough to reduce fixation by a great extent. However, these warnings instructed students not to use the flawed features, without providing any details about the reason behind the instruction. It can be argued that the curiosity of students to explore the reason behind the warnings lead them to the use of those features in their initial designs. It will be interesting to see the extent of fixation in a group where the students are given detailed reasons for the warnings provided to them. This is left for future work.

These results have very important implications for engineering design and education. The reaffirms the presence of design fixation, consistent with many prior studies [12-14, 25, 34, 107]. This also shows that educators need to be very careful in selection of examples for teaching their students. Students can fixate to unwanted or unreliable features in a poor example, which may adversely affect their learning. Providing a flawed example with warnings about the flawed features in that example need not be always helpful in the learning process.

Mitigation of Fixation Hypothesis

The results provide strong support for Mitigation of Fixation Hypothesis. It can be observed that as the students build and test their models, they make changes to their ideas and their final designs contain a significantly lower relative percentage blocks. The occurrence of flawed design features are much less in the final designs for all groups compared to the corresponding initial ones. This shows that the groups fixate to the flawed features in their initial designs and mitigate this fixation through building physical models of their ideas.

The use of physical models at the early stages of design needs to be encouraged. Physical models allow designers to identify the flawed features in their designs and eliminate them. Many times, these flawed features appear in their designs due to their design fixation to example features. The results show that physical models have the potential to mitigate this fixation by a great extent. They allow designers to understand their mistakes by practice.

These results also highlight the importance of a build and learn approach in engineering education. Being able to build prototypes of their ideas and identify the undesirable features themselves can contribute to their learning in a more effective way. As students build and test their designs, they receive instant feedback about their designs and can immediately understand the problems with their designs. This “make mistakes and learn” approach is very close to the “reflection in action” plan adopted by some educators [82, 108, 109], which can prove to be a very effective way for engineering education.

Conclusions

The studies presented in this chapter investigate the presence of design fixation due to poor examples and mitigation of the same through a “build and test” approach. Two hypotheses are investigated in these studies: (1) Fixation Hypothesis which states that students fixate to the negative features of a provided poor example and educators can mitigate this fixation by providing warnings about these negative features (2) Mitigation of Fixation Hypothesis which states that students who build and test their ideas mitigate their fixation to the negative features through building and testing physical models of their ideas. To investigate these hypotheses, two studies are conducted: a pilot study and a full study. The full study rectifies some limitations in the pilot study. In this study, the students building physical models for their class project are grouped into three and each group is provided with a different kind of example. One group receives an effective example, the second group receives a flawed example with three flawed design features and the third group receives the same flawed example with a warning about the undesirable features. The occurrence of the flawed features in their initial and final designs is recorded. The results show that students do fixate to the flawed features of the example and the warnings about these flawed features do not help to mitigate the fixation. At the same time, as they build and test the models of their ideas, they realize the flaws caused by the undesirable features and correct them, leading to a smaller chance of occurrence of those features in their final designs. These provide support to both the hypotheses. These studies also demonstrate a critical function of prototyping in the design process. It allows designers to identify ineffective features of their designs and improve them. Engineering students need to be taught about the potential for design fixation and how to mitigate it. This study also highlights the need of encouraging students to build their ideas and learn through the instant feedback from their testing.

CHAPTER VII

DEVELOPMENT AND TESTING OF PHYSICAL MODEL ERROR REDUCTION METHOD

From the studies discussed thus far in this thesis, it is clear that building and testing physical models help designers in understanding the flaws in their designs and lead them to more functional designs. However, due to the Sunk Cost Effect, it is advantageous to spend least amount of time on physical modelling, to maximize its benefits. Building upon these insights, the work explained in this chapter explores the problems faced by graduate designers in their industry-sponsored design projects. A content analysis is performed on their design reports with a focus on their prototyping. Using this method, the errors that designers frequently commit in their physical modelling stage are identified. In general, these errors lead designers to spending extra time, money or effort on the project, increasing associated cost. According to the results from the controlled studied described earlier in this thesis, increased cost is associated with the higher design fixation. This necessitates a design method to reduce the occurrence of such errors in design projects. With this target, a set of guidelines is formulated. Furthermore, to solve two of the most critical issues, failure to account for all critical loads on the system and failure to design interfaces of components, a novel design method is created and tested. The guidelines and the method attempt to reduce the cost associated with the building process, potentially improving the benefits of utilizing physical models.

Role of Physical Models in Graduate Design Projects

As discussed in Chapter V, physical models supplement the mental models of graduate designers and lead them to changes that improve their concepts. At the same time, they fixate to their initial ideas during physical modelling. This can be explained using Sunk Cost Effect. Compared to the Paperclip Experiment, the design problems being solved by the graduate design teams are more complex and they spend considerably longer time prototyping their ideas. As they spend longer time on each idea, the associated sunk cost is higher which leads them to fixation. In this process, the errors they commit during physical modelling may play an important role. Many errors lead them to re-modelling and thereby increase the associated sunk cost. Hence a set of guidelines and an error reduction method in physical modelling necessitate themselves.

In order to understand the uses of physical models and the errors committed by graduate design teams during physical modelling, the data collected from a project-based graduate design course are qualitatively analyzed. These data contain lot of information relevant and irrelevant to the questions being investigated. It is essential to categorize these data using a qualitative analysis technique before they are ready to be interpreted. A content analysis technique is employed for the analysis. The data in the form of textual information, pictures and tables are included in the content analysis. In order to mitigate the errors observed, a set of guidelines and a design method are formulated. The subsequent sections provide details of the content analysis and the development of the Model Error Reduction Method (MERM).

Design Teams and Data

The data were collected during three different semesters of a graduate design course taught at Texas A&M University. In this one semester course, the students completed a team project by applying engineering design theory based on Otto and Wood [6]. In this course, the teams went from gathering customer needs to proof of concept models with more focus on idea generation. The teams typically consisted of 3 or 4 students, but two students from two different semesters chose to work alone. Project topics ranged from industry-sponsored issues to projects solving design problems from developing countries. By the end of the course, each group had built a working proof-of-concept model and had presented it to the instructor and their sponsor. They were allowed to create either physical, virtual, mathematical, or any other type of proof-of-concept models. There were five teams in the first semester, seven teams in the second semester and five teams in the third. Out of these, four teams utilized only virtual models as proof-of-concepts; hence, their data were not included in the analysis.

The data were collected from each team's final report and two specialized templates designed for the study explained in Chapter V. As explained in Chapter V, these templates captured changes made to the ideas during the physical modeling stage of the project. Additionally, the templates asked the teams to report the motivation for the change. Considering the data, it was observed that the design teams identified many difficulties with their ideas during construction; moreover, as reported in the templates, these problems led to changes in the original design. Consequently, one might conclude that the templates provided rich and relevant information regarding the difficulties faced by designers during physical modeling. In the analysis used in Chapter V, a hypothesis-testing approach is used; the coding scheme is formulated based on the hypothesis and the relevant data are classified using those codes. In the content analysis used in this study, the approach was more towards hypothesis-forming rather than hypothesis testing. The data are classified into categories without any pre-conceptions about the categories. Then these categories are studied further to identify the perceived and actual uses of physical models and the errors designers make during physical modeling.

Content Analysis Procedure

A content analysis [110] was performed on the data obtained from the reports and the templates. During content analysis, all the information (textual, tabulated and graphic) relevant to physical models or physical modelling were concatenated. The graphic information relevant to physical modelling was converted to textual form based on the interpretation of the coder. Next, the texts were divided into stand-alone units (consist of one or more sentences) that convey a concept. These units were printed on index cards. Based upon the judgment of one of the authors, these index cards were sorted into groups. In some cases, a single index card could belong to more than one group. A group contained index cards with information regarding a particular aspect of physical models. For example, many cards talk about the designer's perceived uses of physical models; they all are sorted to the same group. These groups were very general (For example, physical models replicate the behaviour of the actual system; the cards in this group may come from various contexts, but these contexts were not considered in the analysis), and any cross reference to the origin of the text was avoided to eliminate bias in sorting. Following categorization, the categories were reanalyzed and combined to eliminate dependencies and increase categorical differences. For example, one group of cards talked about physical models helping designers in the identification of missing dimensions, while another group talked about physical models revealing some unexpected behaviour of the system. In these cases, both groups essentially dealt with the actual uses of physical models. Hence they both are classified under the larger group with actual uses of physical models. This re-sorting provided the themes/trends associated with physical modelling. The obtained themes and the groups forming those themes are shown below (All the groups obtained are listed here; some of them are not important for the further studies).

Perceived Uses of Physical Models:

- Physical models were built to test a part of the whole system
- Physical models were used to infer the effectiveness of an idea
- Physical model was employed to check the functionality of an idea
- Prototypes were used to check the feasibility of using a material for building a part
- Physical model was used to determine the target value of a performance parameter

- Physical model was built to measure forces/torques within the system
- Physical models were used to determine the dimensions/position of a component in the system
- Physical models were used to infer the ergonomics/ease of use
- Physical model was built to replicate the behaviour of the actual system
- Physical models were used for motion studies
- Physical models were built to measure deformations
- Physical models were built to check the effects of factors biasing the performance of the idea
- Physical models were used to communicate ideas to the customer

Observed Uses of Physical Models:

- Physical models helped to test an idea and collect data
- Physical model proved that the idea could satisfy the performance requirements
- Physical models lead design teams to modifications that improved the idea
- Physical models showed a different, but better way to solve the problem
- Physical models suggested that an idea could not satisfy the requirements.

- Physical models suggested that the material of construction was not appropriate
- Physical models revealed some totally unexpected phenomenon/behaviour of the system
- Physical models revealed flaws in the idea
- Physical models disproved initial assumptions
- The building process showed the necessity of specific configuration of parts/material which was not thought of earlier
- Physical models showed that one configuration (of the same idea) is better than others
- Physical model showed the advantages of one idea over the others
- Physical models showed the necessity of further testing
- Physical model confirmed a doubt/confusion at the beginning of modeling
- Physical models provided insights for improvements of an idea
- Building process led to new theories about the solution
- Physical models showed that parts could not be assembled as expected
- Physical models showed the necessity of new pre-requisites

- Physical models raised concerns about the cost vs performance of the idea
- Physical model raised safety concerns for the user

Conceptual Errors in Physical Modeling:

- Failure to consider one or more critical load, leading to the failure of the part/parts of the system
- Failure to design physical interfaces of two or more parts (connections) leading to the failure of the assembly
- Improper planning of available time or budget, leading to inefficient utilization of resources
- Hesitancy to significantly modify parts after failure (Fixation to existing parts)
- Use of a complicated measurement system when a simpler one is available
- Building new parts when standardized parts are available for purchase at a lower cost
- Building physical models to obtain information that is available from other cheaper/faster sources (e.g.: Literature)
- Failing to properly scale loads when the parts are scaled
- Selection of materials (especially to reduce material cost) that require costly

machining which leads to a higher overall cost

Practices in Physical Modeling:

- Analytical calculations were performed to support the building
- Theory was used to support/ease building process and to select initial configuration
- Initial assumptions were made to simplify the building process
- Physical models were scaled down/up versions of the actual idea
- To build the model, parts of a readily available machine/part were modified
- Materials available easily in locality were used to build the models
- Special parts were purchased and machined to make the actual product prototype
- Specific material was selected to ease machining
- Specific material was used to restrict deformations
- The number of parts was minimized to reduce machining time and cost
- Step-wise addition of parts to reach final configuration was employed to save some testing
- Specific order of construction was followed for ease in manufacturability

- Idea was modified so that a readily available machine/part could be used in the building
- Idea was modified to adjust with the limited availability of materials
- Measuring gauges were pre-mounted to obtain accurate measurements
- Complicated measurement systems were replaced with simple/easy to use measurement techniques
- Complicated parts/systems were replaced with simpler ones to simplify the building process
- Used averages (of configurations) to make the testing process easier
- Some attributes of the idea were ignored to simplify the building process
- Initial configuration was modified to make the idea work
- Parts were modified during the building
- Construction material was replaced with a better one
- Some parts were modified for ease in handling
- Tests were repeated in multiple orientations/configurations to ensure generalizability
- Physical model was built by simplifying the system to test specific aspects

- Avoided same person taking multiple measurements to prevent measurement bias
- The model was redesigned to be able to use with multiple samples

The first two themes show the perceived and actual uses of physical models in design projects. These themes highlight the importance of using physical modeling as a part of the design process. The third theme shows the major conceptual errors that designers commit during the building of physical models. These errors lead designers to spend more time, money or effort in building and thus increase the associated cost. In some cases, these errors can lead to the failure of a whole concept. In order to maximize the advantages of physical models, it is essential to mitigate these errors. Therefore, this theme is considered in more detail in this chapter. The last theme shows the common practices in building physical models and this includes some good practices too. This theme is also used to derive the guidelines for physical modeling.

Formulation of Guidelines for Physical Modeling

Based upon the conceptual errors discussed in the previous section and various observations concerning the effective practices (listed in the "practices in physical modelling" theme in the previous section) utilized by the design teams, observations and insights from the other studies in this thesis and the literature explained in Chapter II, a set of guidelines was formulated. Each good practice included in the "practices in physical modelling" theme is carefully considered against the conceptual errors to identify how these practices can eliminate such errors. Table 13 lists the resulting guidelines. These guidelines aimed to reduce the observed conceptual errors and decrease the total cost associated with the building process.

Table 13: Guidelines for building physical models formulated from the analysis

1	Support building with analytical calculations - use basic strength equations for calculations
2	Design the connections (interfaces of parts) before commencing construction
3	Plan the building process – in terms of time and budget
4	Combine superior features from multiple solutions(before/after building or both)
5	While scaling the model, scale loads accordingly
6	Be aware of unexpected phenomena during building
7	Wherever possible, use commonly available parts (available in the immediate environment)
8	Wherever possible, avoid complicated machining
9	Wherever possible, select materials that can be easily machined
10	If standardized parts are available, use them instead of building new ones
11	When using parts of standardized (fixed) length (e.g. Legos), make sure that other dimensions change accordingly
12	Use simple measurements (e.g.: visual) if complicated measurement techniques are not necessary

Development and Testing of the Model Error Reduction Method

From the list of conceptual errors mentioned in the previous section, the two critical ones are: failure to include critical forces in design and failure to design connections of parts. If present in the design, these two conceptual errors can lead to the failure of part(s) in the system or the failure of the entire design. Since the rectification of these two conceptual errors might involve redesigning the system, these issues typically involve comparatively higher costs (in terms of money, time and effort).

To develop a design method which helps designs to rectify the two most critical issues, it is assumed that, if designers are forced to think about each force and connection in their design, the quantity of functional designs will increase. Consequently, the Model Error Reduction Method involves two templates as shown in Figure 46 and Figure 47. These templates are to be filled out by the designers once the conceptual design is complete but before the beginning of the building process. Template 1 forces designers to draw complete free body diagrams of each part and list the forces drawn on the free body diagrams in a table. Also, designers note down whether they considered the forces in their designs before using the template. Template 2 attempts to encourage the design of the connections involved in the system. It asks the designers to draw the free body diagram of each connection, marking the forces on the parts. Later, the designers are asked to note down the forces in the table below. Following this, the designers are asked whether they considered the contact forces in their design before using the template. Both templates instruct designers to go back and incorporate any missing forces in their design.

Part name/number:
Free body diagram: (You may annotate your forces and use these annotations in the table below)
List the forces that you drew on the free body diagram in the following table:

Force acting on the part	**Type of force (tension, compression, bending, shear etc.)**	**I considered this force in my original design (Y/N)**

Figure 46: Template 1 of the Model Error Reduction Method

Part name/number:
Part name/number:
Free body diagram: (of the two parts showing the forces between them - You may annotate your forces and use these annotations in the table below)
List the forces that you drew on the free body diagram in the following table:

Force acting on interface	**Type of force (tension, compression, bending, shear etc.)**	**Part on which the force acts**	**I considered this force in my original design (Y/N)**

Figure 47: Template 2 of the Model Error Reduction Method

Evaluation of the MERM- Experiment Method

In order to ensure the effectiveness of these templates, a controlled experiment is designed and conducted. The controlled experiment tests the following hypothesis:

The use of the two templates motivates designers to rethink about their design calculations, helping them identify forces missing from said calculations. The controlled experiment testing the effectiveness of the Model Error Reduction Method templates follows a within-subject design. In the experiment, novice designers design a familiar mechanical system without the help of the templates. Later, they are instructed to fill out the templates and make the necessary changes in their designs. The scope of the changes made to the designs as participants complete the templates is studied to infer the effectiveness of the method. A more detailed description of the experiment follows.

Participants

The participants in this experiment were senior undergraduate students in the Mechanical Engineering Department of Texas A&M University. They were recruited through class announcements. Twelve students volunteered for the experiment. Three of them were female. The participants were screened before the experiment to ensure that they had completed their courses on mechanical design of machine elements. This ascertained that each participant a similar same level of expertise in mechanical design. None of the participants possessed more than 6 months of industrial experience. For participating, each person received either monetary compensation or extra credit in one of their classes.

Design Problem

Each participant was asked to develop a detailed mechanical design for a bicycle. They were given a concept sketch for a bicycle design (Figure 48). The problem instructed them to develop a detailed design for the system as a whole and the components involved. Participants were allowed to make any necessary assumptions. No specific constraints were provided to them, but they were asked to list the steps they followed with the help of diagrams and descriptions. They were also instructed to state their assumptions and list the equations they utilized. They were told not to consider the seat, spokes and wheels in their design. They were also instructed to treat each member of the frame as a separate part. Since the final numerical values were not of interest in this experiment (the interest was on the design procedure), estimates of the dimensions of each part were available to the participants.

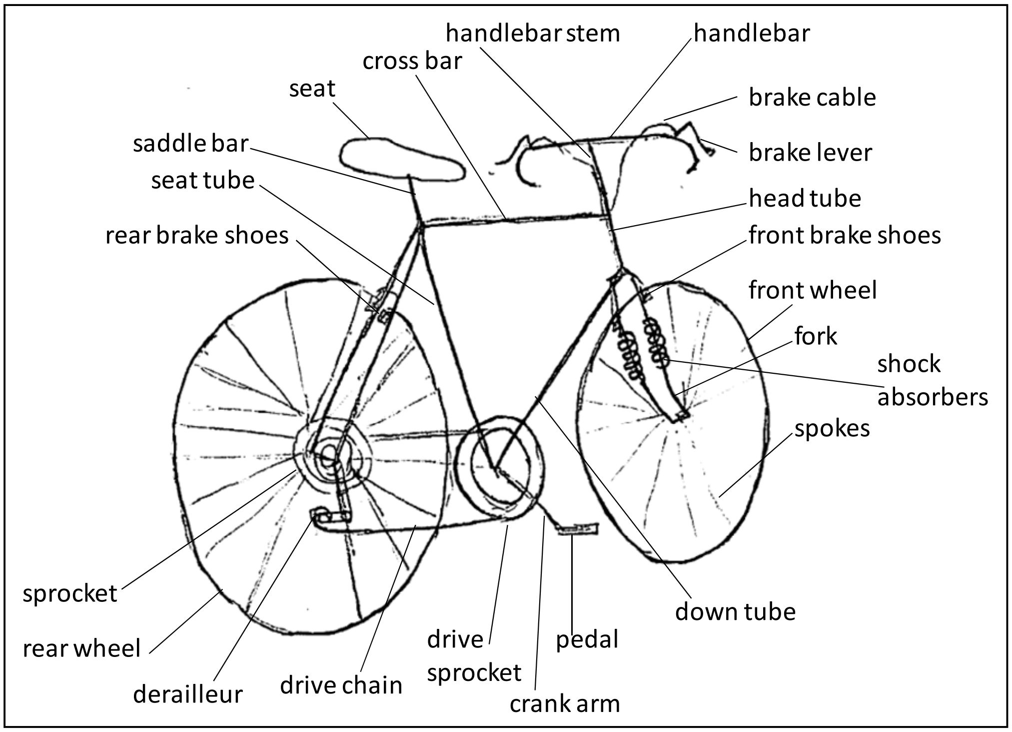


Figure 48: Bicycle concept provided to the participants in the experiment

The bicycle design problem was selected for this experiment due to its sufficient complexity and the likelihood of participant experience with the device itself. If the design problem was too simple or contained too few parts, measuring the effect of the templates would be difficult. The bicycle problem was difficult to finish within the allotted time of the experiment, but participants were asked to only fill the templates out for the parts finished. Such a tactic avoided any bias due to an incomplete design.

Experiment Materials

The experiment involved three different activities, and in each activity the participants received a different set of materials. In the first activity, the participants were provided with the problem statement, instructions and a few blank sheets of paper. The participants were allowed to use as many sheets as they desired and were instructed to number the sheets in the order of their use. In this activity, the participants also received a copy of "Shigley's Mechanical Engineering Design" textbook [111] and a calculator. In the second activity, the participants received copies of Template 1 and a different color pen to write with. The different color pen enabled easy tracking of any changes they made to their original design from the first activity. In the last activity, they were provided with copies of Template 2 and a pen with a third color. The problem statement and the original design were available to the participants throughout the experiment, and they were encouraged to make changes to the original design.

Procedure

As the participants entered the experiment room, they were guided to their seats. Up to two participants underwent the experiment at the same time, but their seats were separated by curtains. As the experiment began, participants received the design problem and the instructions (See Appendix E). They were given 90 minutes to work on the design. Since completely designing the bicycle in 90 minutes was nearly impossible, they were instructed to complete as much of the design as possible in the time provided. They were given 5 minute breaks 50 minutes into the design and at the end of the design. After the second break, the participants were given copies of Template 1. They were instructed to fill the templates out for each part completed during the first activity. They were also told to mention whether they had considered all the forces in their free body diagram during the original design stage. If they did not, and if they thought that force was important, they were allowed to go back and make changes to the original design. This activity lasted for 30 minutes. In the third activity, participants filled out Template 2. They were required to complete template 2 for each connection in their design. Also in this activity too, they were allowed to go back and make changes to their original design. This activity too lasted for 30 minutes. Participants were allowed to move on if they finished any activity before the time limit was reached. At the end of the experiment, they were asked about any previous industry experience.

Metrics for Evaluation

Two different metrics are employed to evaluate the effectiveness of the design templates: Number of extraneous template forces and number of design modifications. The method templates help designers in identification of forces not considered in their original design and prompt them to modify their designs including those extraneous forces. The number of extraneous template forces is defined as the number of forces listed by the participants in their design templates minus the ones already considered in their original design. This metric is calculated separately for the two templates. Number of design modifications measures the number of changes that the participants make to their original design as they use the templates. This metric also measures how many of the extraneous forces identified by the templates are perceived to be important by the participants. These forces are likely to be missed by the participants during their original design. These two metrics together provide valuable insights about the usefulness of the design method developed.

Experiment Results and Discussion

The results obtained for the metrics show that the newly developed design templates provide an effective way to perform design calculations. A more detailed description of the results for each individual metrics is provided in the following sections.

Number of Extraneous Template Forces

It is observed that as participants use the method templates, they list many forces that they have not considered in their original design. Figure 49 shows the mean number of extraneous forces identified by the participants from each template. It is observed that majority of the participants fail to produce complete free body diagrams of the parts or connections they design, which leads them to missing forces in the calculations. As the design templates force them to draw a free body diagram for each part, they identify those missing forces.

A paired-sample t-test [112] is conducted to analyze the data statistically. This test confirms if the number of extraneous forces identified is statistically different from zero. The results show statistical significance for both the templates (for Template 1: $t = 2.98$, $p = 0.01$; for Template 2: $t = 3.91$, $p < 0.01$). This result confirms that in significant number of cases, the templates help designers in detecting extraneous forces in their designs. It also confirms that the templates satisfy their intended purpose of helping designers in identification of missing critical loads in their designs.

Number of Design Modifications

From the data, it is observed that the participants make many changes to their original design based on the extra information gained from the method templates. Though the templates provide them the extraneous forces, the participants do not include all those forces in their design. They include only those forces they perceive to be important for their design. Figure 49 shows the number of modification resulted from the individual templates and from the whole method. Only the changes that contribute significantly to the design are counted (for example: addition or deletion of the forces, modification of points of action of forces etc.).

A paired-sample t-test is used for the statistical analysis of these data too. The results show that the number of design modifications is statistically significant (From Template 1: $t = 2.27$, $p = 0.04$; From Template 2: $t = 2.09$, $p = 0.06$; Overall: $t = 2.51$, $p = 0.03$). This shows that the method templates prompt designers to make significant number of changes in their design. This result provides strong support for the presented hypothesis and shows that the new method is effective in helping designers with their calculations for building physical models.

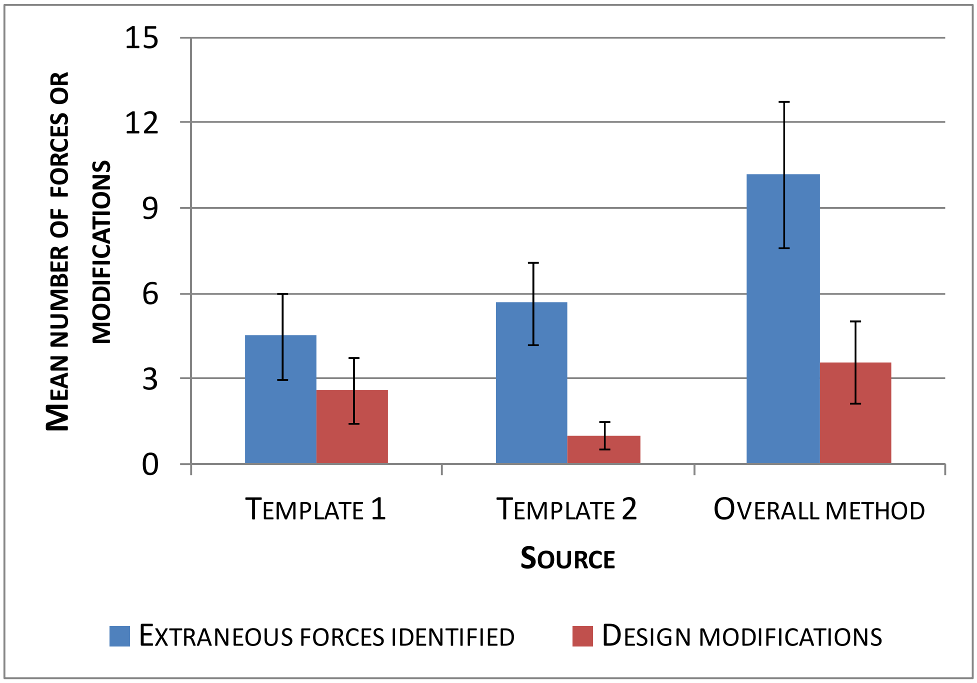


Figure 49: Mean number of design modifications due to the method

It is observed that though the participants identify more extraneous forces from Template 2 compared to Template 1, majority of the design modifications result from Template 1. This shows that the participants perceive the contact forces to be less critical compared to the forces on the parts. This may not be true in all design calculations. Forcing the participants to calculate the values of these forces and make the decisions based on the values may eliminate this difference.

Limitation of the Model Error Reduction Method

The Model Error Reduction Method introduced here is shown to be very effective by the experiment results; however it possesses a limitation. This method is useful only for structural calculations as it mainly deals with forces on the parts and systems. However, in many cases, design of mechanical systems includes calculations from other disciplines like thermodynamics, fluid mechanics, chemical and material science etc. The current method cannot deal with such calculations; however, it can be easily modified to include these too. This needs to be completed in future work.

Conclusions

Physical modeling is considered to be an efficient tool in engineering design as it helps to reveal the flaws in the ideas. This paper discusses the perceived and actual uses of physical models in graduate design projects along with the conceptual errors that novice designers face as they build physical models of their design concepts. These conceptual errors lead them to a higher building time and thus affect the effectiveness of physical modeling. To rectify this, a set of guidelines for physical modeling is proposed. A Model Error Reduction Method solves two critical errors (failure to consider critical loads in their design and failure to design physical interfaces) that novice designers make is formulated and tested. The test results show that the newly formulated design method is effective in rectifying the said two conceptual errors. However, the method needs to be expanded to include more problem domains.

CHAPTER VIII

ROLE OF EXPERTISE IN DESIGN FIXATION – THE FIXATION EXPERIMENT

The studies discussed in chapters II to VII employ controlled and qualitative experiments on novice designers to understand the cognitive effects of physical models on engineering idea generation. As explained in Chapter VII, the results from these studies are employed to develop a set of guidelines and a new design method to aid the use of physical models. In real world, the designers may have varying levels of expertise in generation of ideas and their behaviour in idea generation process may vary depending on their experience. Hence it is essential to consider the role of expertise in engineering idea generation. The study described in this chapter compares the ideas generated by design experts and novices to identify any difference in the amount of design fixation.

Hypotheses

Based on the background literature depicted in Chapter II, the following hypotheses are proposed in this chapter and investigated further:

Expertise Hypothesis: *Experts with practical experience in solving creative design problems have a broader knowledge, which will form their initial solution space and hence they will outperform novices in terms of quantity of ideas.*

Fixation Hypothesis: *Experts with practical experience in solving creative design problems will fixate less to examples compared to novices.*

Method

The study described in this chapter compares the idea generation performance of design experts with that of novices. Based upon the stated hypotheses, it is expected that both experts and novices to fixate upon features of the provided examples; nevertheless, experts should outperform novices in terms of the quantity of ideas. To investigate the hypotheses, the experimental conditions described by Linsey et al. [13] are recreated with novices. In the subsequent sections of this chapter, the prior experiment by Linsey et al. [13] is referred to as the "expert study" and the corresponding data as the "expert data." Since the new experiment utilizes novice participants, it is referred to as the "novice study" and the data as "novice data." In the expert study, the participants are mostly design faculty who have considerable experience in solving design problems. In novice study, the participants are senior undergraduate students with limited practical exposure to solving open-ended design problems. All the participants, in both the studies, solve the same design problem and are randomly assigned to the experiment conditions. The details of these conditions and the design problem are described in the sections to follow.

The novice study and the expert study differed in several minor aspects which should not influence the overall outcome of the experiments. Participants' expertise level was expected to be the single factor influencing the outcomes. The environments, in which the experiments were conducted, were different. The expert study was conducted as a part of an NSF sponsored design workshop. The novice study was conducted as a class exercise in a senior undergraduate design course. Also, the participants in the novice study received either extra credit or monetary compensation. Idea generation during the expert study was 45 minutes, whereas the novice study allowed 40 minutes for idea generation. To account for this difference, the metrics used for comparisons were normalized with the idea generation time in minutes. In the expert study, a post-experiment survey was given to the participants; but, due to time restrictions, this was not done in the novice study. Obviously, the ideal experiment involves both the novices and experts generating ideas in perfectly matching conditions. Unfortunately, a large sample size of expert data is difficult to obtain. Since this study compares new data to existing data obtained under extremely similar conditions, one can conclude that the comparison is acceptable.

Design Problem

Both expert and novice participants generated ideas for the same design problem. The design problem instructed them to design a device capable of quickly shelling peanuts capable of functioning without electricity. Also included within the problem statement was a list of customer needs. Succinctly stated, the device must be easily manufactured and capable of shelling and processing the peanuts in large volumes, in a minimum amount, with a minimum amount of damage and at a low cost. Figure 50 shows the design problem statement provided to the participants.

This problem attempted to replicate the challenges of solving a real-life, open ended problem. In the expert study, the post-experiment survey asked participants about their familiarity with the problem. A total of seven participants, evenly distributed across the conditions had prior exposure to the design problem. Four of them confirmed that they were exposed to the solutions to the problem too. However, they rated their exposure as not significant enough to cause any bias in the results. Since these participants were evenly distributed across the conditions, this prior exposure was not considered as a biasing factor. In novice study, the experimenter asked the participants about their prior exposure to the problem. Two participants confirmed that they had participated in prior idea generation tasks with the same problem and therefore their data were excluded from analysis.

Design Problem - Device to Shell Peanuts

Problem Description:
In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal 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.

Figure 50: Design problem description provided to the participants

Experiment Conditions

The participants were randomly assigned to three different experiment groups: the Control Group, the Fixation Group and a Defixation Group. Each of these groups is described, in detail, below:

Control Group

The control group was provided with the design problem and asked to generate as many solutions as possible. They received plain sheets of paper to record their ideas. Also, they were instructed to label parts of their ideas and provide a 1-2 sentence description of the way in which each idea functioned. The participants were also encouraged to record any thoughts or comments as they generated their ideas. They were not provided with any additional materials.

Fixation Group

The Fixation Group was provided with the same design problem and instructions as the Control Group plus an example solution. The example solution is shown in Figure 51. A short description of the solution was also given to the participants which read as: “This system uses a gas-powered press to crush the peanut’s shell. The shell and the peanut then fall into a collection bin.” This solution possessed several shortcomings. First, the use of a gas powered press would decrease one’s control of the damage done to the peanuts. Second, the system, as a whole, was too complicated and expensive for use in an African country. Though these disadvantages were not explicitly stated, the participants could easily infer as much from their Mechanical Engineering background. In the original expert study, the authors chose the example based upon features commonly found in participant solutions from prior experiments [90, 91]. Prior studies have shown that common solutions tend to fixate designers more [113, 114].

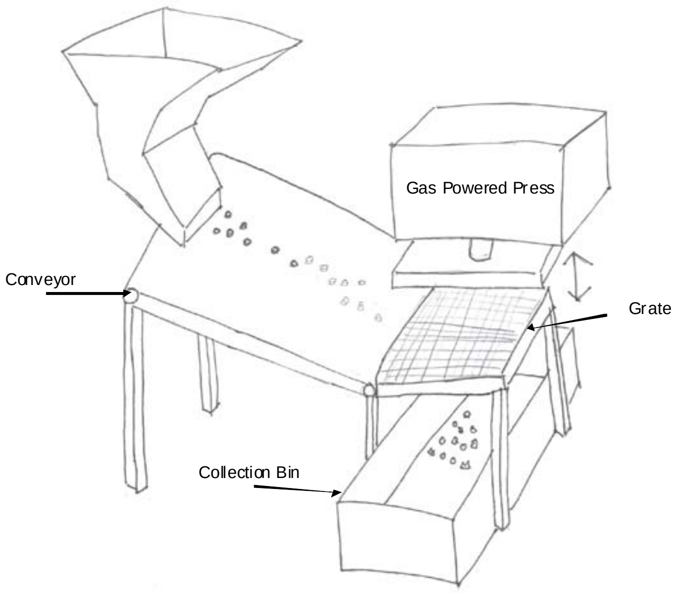


Figure 51: Example solution provided to the participants in the Fixation and Defixation groups [13]

Defixation Group

Participants in this group were provided with the same design problem and instructions as the Fixation group plus the defixation materials shown in Figure 52. The defixation materials included alternate representations of the design problem, a brief functional description of the problem, several useful analogies that could help solve the problem and a list of alternate energy sources. It also possessed several "back-of-the envelope" calculations. These materials were expected to help the participants mitigate the fixation from the example solution. The analogies were originally developed for the expert study using the WordTree Design-by-Analogy method [115] with the keywords "remove" and "shell."

Participants

The expert study was conducted as a part of a NSF sponsored workshop entitled "Discussion on Individual and Team Based Innovation" by Linsey et al. [13]. Thirty-one engineering academics volunteered for the workshop. Most of these participants possessed experience in academia and were researchers in the field of Engineering Design. The vast majority of them also had industry and consulting experience. The majority of the participants had a mechanical engineering background, and 33% of the participants were female. These participants were distributed randomly across the experimental conditions. For the expert study, the Control Group had nine, the Fixation Group had twelve and the Defixation Group had ten participants.

To assist you in developing as many designs as possible, consider the following clarification to the problem:

Functions:
- Import natural or human energy to the system
- Convert and transmit energy to peanut
- Remove peanut shell (remove outer structure from inner material)
- Separate removed shell (outer structure) from peanut (inner material)

Example Analogies that You Might Find Helpful:
- Hull
- Shuck
- Husk
- Clean (clean a deer, clean a fish or scale a fish)
- Soak
- Heat, Roast
- Dissolve
- Pod
- Pit, stone
- Burr (deburr something)
- Ream
- Bark (bark a tree)
- Skin
- Pare apples
- Pluck, deplume (strip feathers)
- Peel
- Grind (like a nut grinder)
- Brittle fracture

Natural Energy Sources Available:
- Wind
- Solar
- Running water streams
- Captured rain water at a height
- Solar
- Human
- Animal

Back-of-the-envelope Calculations:

A quick analysis shows that a much greater quantity of power (or force) is needed to act on many peanuts simultaneously compared to applying power to a few peanuts at a time.

Figure 52: Defixation material provided to the participants in the Defixation Group [13]

The novice study was conducted as a class exercise during a regular class period of a senior undergraduate capstone design course. All the participants in this study were senior undergraduate students from the Mechanical Engineering Department at Texas A&M University. Participation in this study was completely voluntary. Thirty-one students volunteered for the experiment and were randomly assigned across the Control, Fixation and Defixation groups. There were ten participants each in the Control and Fixation groups and eleven in the Defixation Group. One participant each, from the Control and Defixation groups, confirmed that they were familiar with the design problem through another idea generation activity. Consequently, their data were removed from analysis. Out of 31 participants, seven were female. The participants received either extra class credit or monetary compensation for their participation.

Procedure

When the experiment began, the participants received the design problem and the additional materials, if any, as determined by the condition. The participants were instructed to generate as many solutions as possible for the given design problem. They were told that the participant with greatest number of solutions would be awarded a prize. As the experiment started, both the expert and novice participants were given 5 minutes to read and understand the design problem and the instructions. These 5 minutes were followed by idea generation for the design problem. In the expert study, the participants were given 45 minutes for idea generation; but, in the novice study, idea generation occurred for only 40 minutes. The idea generation time was reduced for the novice study in order to accommodate it within a regular class period. They were asked to draw sketches of their ideas accompanied with short descriptions or comments. They were also instructed to label various parts of their sketches. The participants were requested to record, on the bottom corner of the sheet, the time at which they generated each idea. For the experts, the experiment ended with a post-experiment survey which collected information regarding their prior exposure to the design problem, perceptions about their performance and the influence of the given example solution. In the Defixation Group, the participants were also asked about the perceived usefulness of the defixation materials. For the novices, this survey was not provided due to time limitations. Nevertheless, the experimenter did ask the participants about any prior experience with the design problem. In both expert and novice studies, all the participants received the reward for generating the greatest number of solutions, regardless of the number of solutions they actually generated.

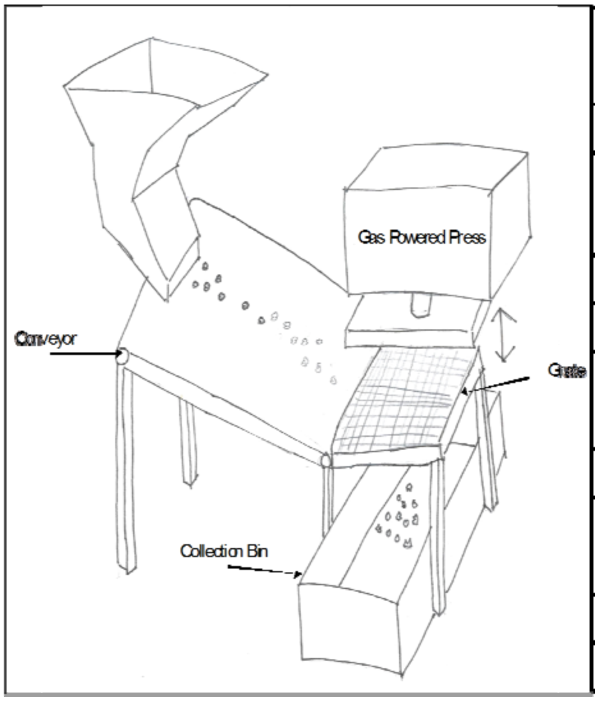
Metrics for Evaluation

To evaluate the hypothesis presented, five different metrics were employed by Linsey et al. [13] in their expert study. The same metrics were used in this study too. These metrics were: (1) Quantity of non-redundant ideas (2) Number of example solution features appearing in the ideas generated (3) Percentage of example features in participants' solutions (4) Total number of energy sources used and (5) Percentage of solutions using gasoline powered engine as power source. The author evaluated all the data for each metric. To ensure consistency in analysis and eliminate noise in the data due to different evaluators, the expert data were completely reanalyzed for this study by the reviewer. An independent evaluator, blind to the conditions, repeated the evaluations for 60% of the data. To ensure reliability of these measures, inter-rater agreement was calculated between the two raters. The inter-rater agreement of these results with the original evaluations from the expert study was also calculated. It was observed that the average inter-rater agreement (Pearson's correlation) between these two studies was 0.87, which showed that the two evaluators analyzed the data consistently. As the idea generation time in expert study varied from that of novice study, all these metrics were normalized with the respective times allotted for idea generation. The prior study by Linsey et al. [91] demonstrated that the rate of idea generation in 30 to 40 minutes and 40 to 45 minutes remained the same. Hence normalizing with idea generation time could eliminate any possible bias from the difference in idea generation time.

Quantity of ideas was based on the procedure outlined by Shah et al. [88] and as further developed by Linsey et al. [13]. For the purpose of this study, an idea was defined as the one which solved one or more functions in the functional basis [104, 116]. Figure 53 shows the example solution provided to the participants and the ideas counted within it. The ideas repeated from the example were considered as redundant ideas. These were eliminated from the list of ideas of each participant and the quantity of non-redundant ideas was computed. An inter-rater reliability score (Pearson's correlation) of 0.82 was obtained for this metric. As this correlation was high [92], the method to obtain quantity of non-redundant ideas was considered reliable.

Another metric used to measure fixation was the number of example features used by the participants. The number of times participants used the features shown in Figure 53 for their solutions was identified. An inter-rater agreement (Pearson's correlation) of 0.83 was obtained between the two judges, showing that this measure was reliable. The number of example features used by a participant was normalized with the total number of ideas generated by the participant to obtain percentage of example features in that participant's solutions. This metric rectified any bias existed in the analysis due to the variation of total number of ideas generated by participants.

Another measure of fixation was the number of energy sources used by the participant. The example solution used a gas-powered press for shelling peanuts. Based on this feature, two metrics were used to measure fixation: the total number of energy sources and the percentage of solutions using gas powered press. The percentage of solutions with gas powered press was calculated as the ratio of the number of solutions using gas engine powered press to the total number of solutions generated. An inter-rater agreement of 0.90 was obtained for this metric. This was high enough, proving this metric was reliable.



Function	**Solution from example**
(Material)	
Guide	Sloped surface, conveyor
Import	Hopper
Position	Table legs
Remove (shell)	Crushing plates
Store	Bin
Separate (nut and shell)	Grate
(Energy)	
Convert	Gas press

Figure 53: Ideas in example solution categorized based on function

Results

This study compares the fixation of expert and novice designers to example solutions. Figure 54 shows a few example solutions with high degree of fixation to the provided example. At the same time, the solutions shown in Figure 55 have low degree of fixation. The five metrics mentioned in the previous section are used to measure fixation quantitatively. Details of these results are available in the following subsections.

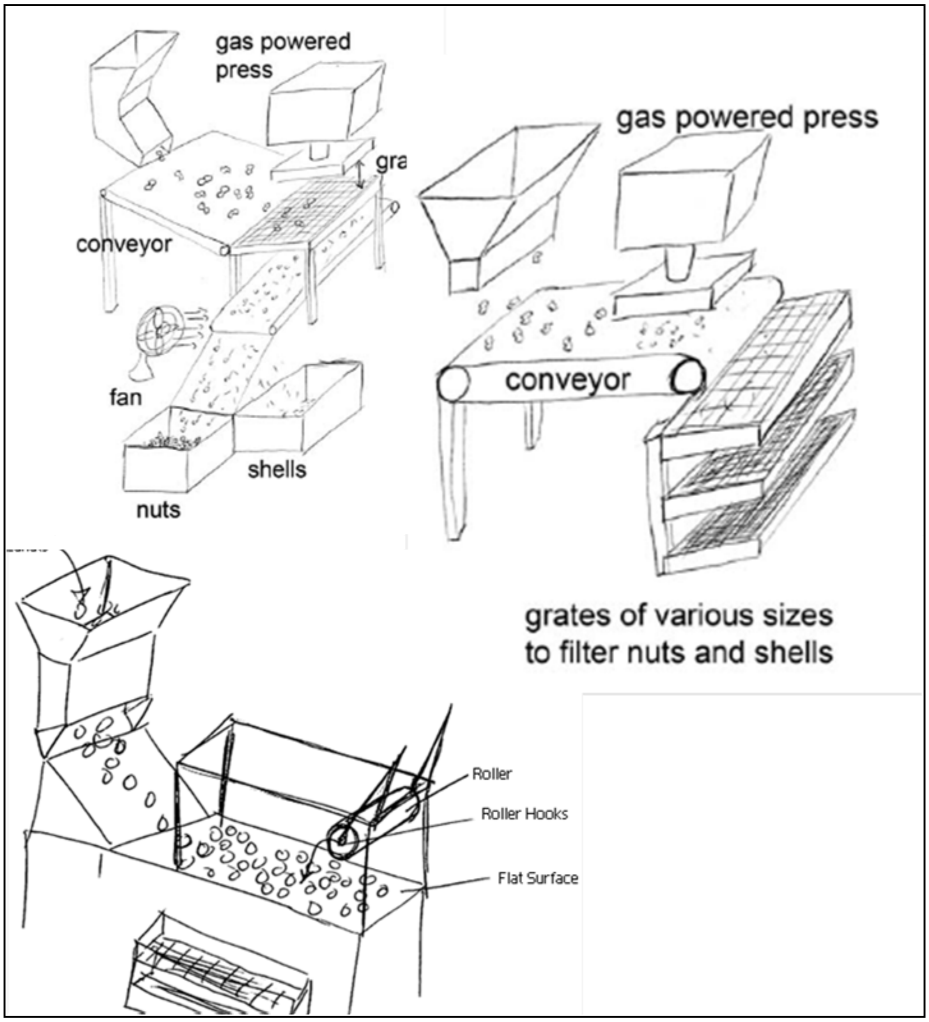


Figure 54: Sample solutions showing high degree of fixation to the example

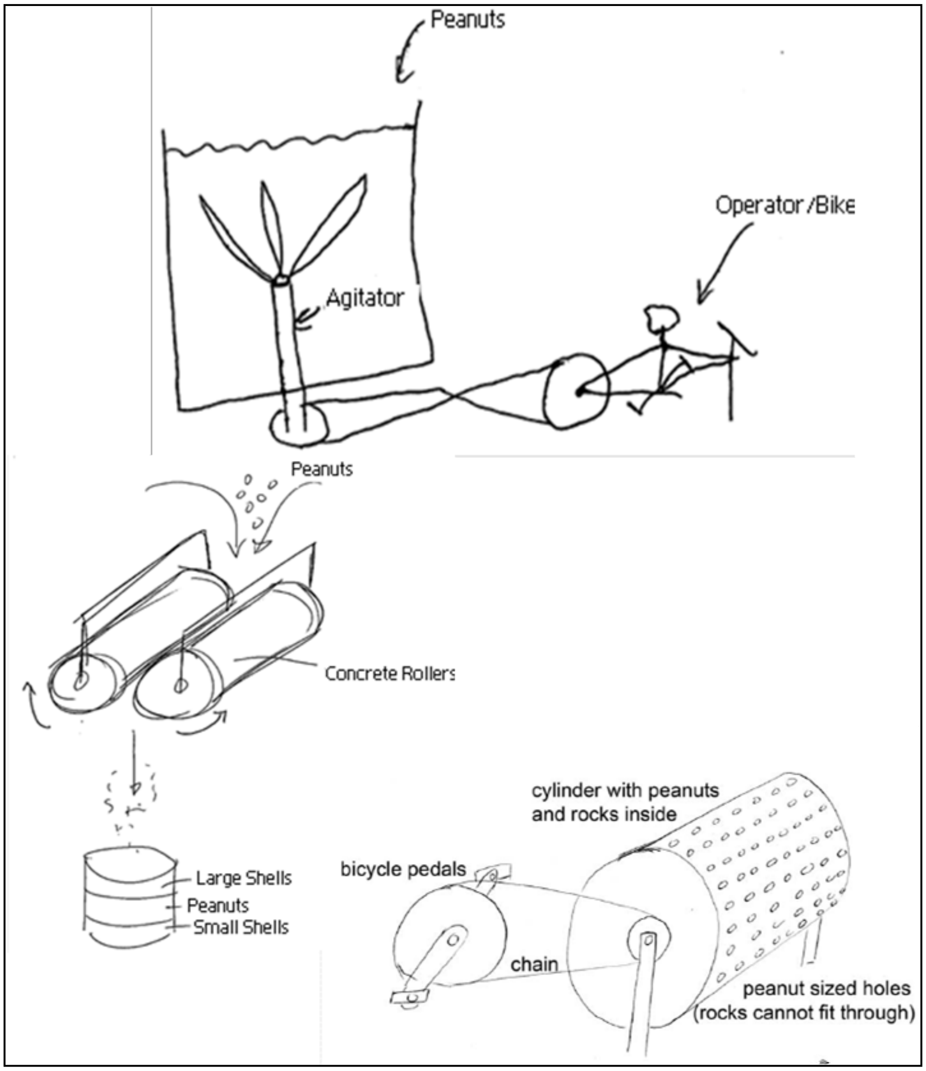


Figure 55: Sample solutions with low degree of fixation to the example

Quantity of Non—redundant Ideas

The results reveal an interesting difference in the mean quantity of non-redundant ideas across the experiment conditions for experts and novices. Figure 56 shows the variation of the mean quantity of non-redundant ideas, generated per minute, across the conditions. Consistent with the results from the expert study, expert participants in the Control Condition generate more non-redundant solutions than those in the Fixation and Defixation conditions. Novice designers in the Control Condition produce significantly less non-redundant ideas, per minute, as compared to the expert designers. In contrast to the results for experts, there is no increase in quantity from the Fixation to the Defixation Condition for novice designers indicating that the defixation materials are not reducing their fixation.

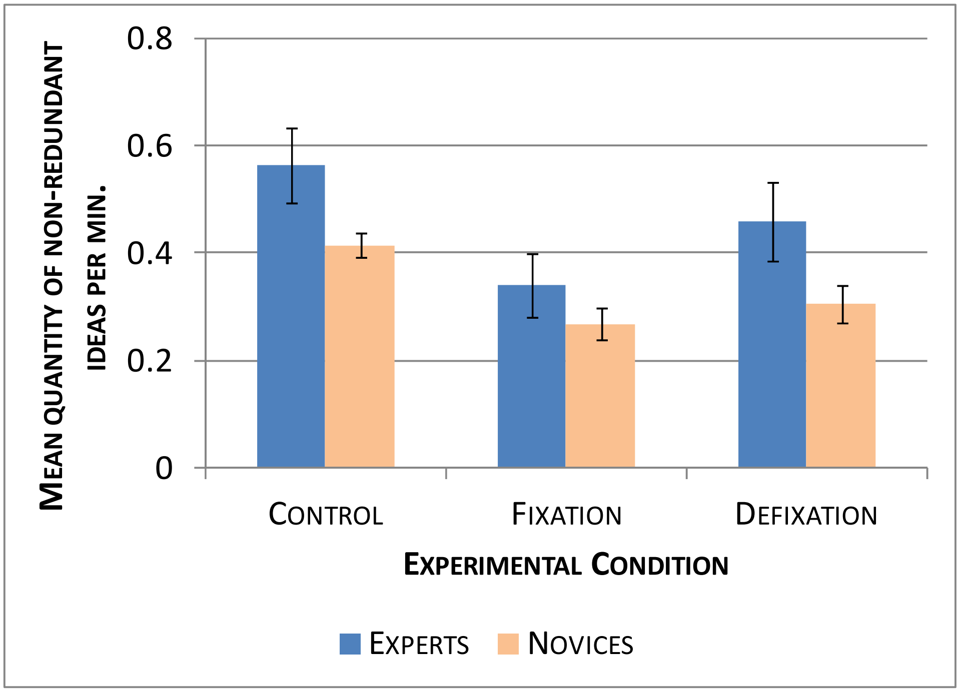


Figure 56: The pattern of variation of the quantity of non-redundant ideas reveals a difference between experts and novices. Error bars show (±1) standard error.

To statistically compare the various conditions in the experiment, a one-way ANOVA is performed on the data. The data is normally distributed but does not satisfy the homogeneity of variance assumption. Nevertheless, the sample size is large enough for ANOVA to be robust despite the violation of this assumption [100]. The results show that the mean quantity of non-redundant ideas, generated per minute, varies significantly across the experiment conditions ($F(5,59) = 4.06$, $p < 0.003$). A-priori t-tests are used for pair-wise comparisons [93], and the results are shown in Table 14.

Table 14: A-priori comparisons for quantity of non-redundant ideas generated per minute

Conditions compared	**p**
Comparisons evaluating the hypotheses:	
Expert Fixation – Novice Fixation	0.32
Expert Control – Novice Control	0.07*
Expert Defixation – Novice Defixation	0.05*
Expert Control – Expert Fixation	<0.004*
Novice Control – Novice Fixation	0.06*
Other interesting comparisons:	
Expert Control – Expert Defixation	0.18
Expert Fixation – Expert Defixation	0.10
Novice Control – Novice Defixation	0.16
Novice Fixation – Novice Defixation	0.62

* Statistically significant comparisons at $\alpha = 0.1$

These results demonstrate that both expert and novice participants, when provided with an example solution, generate significantly less non-redundant ideas as compared to the control group. The novice designers in the Control Condition produce a significantly lower quantity of non-redundant ideas, per minute, as compared to expert designers in the same condition. This result is consistent with the Expertise Hypothesis. An expert's relevant knowledge is comparatively greater than a novice's. As a result, they are able to generate a greater number of ideas during the idea generation activity. Though this is the case, the introduction of the example solution still fixates both experts and novices. This result does not support the Fixation Hypothesis, as both experts and novices fixate to the same extent. Though experts do mitigate their fixation, to some extent, with the help of the alternate representations of the design problem, this result is statistically insignificant for the quantity of ideas produced. In the case of novice designers, the alternate representations of the design problem do not help them mitigate their fixation.

Number of Example Solution Features Used

The results obtained for this metric strongly support the Fixation Hypothesis. Figure 57 shows the variation of the mean number of times the example features are used by the participants, per minute, across the conditions. Although the participants in the Control Condition do not see the example solution, some features from example appear in their solutions. Novice participants in Control Condition use a lower mean number of example features in their solutions. Additionally, both experts and novices, in the Fixation Condition, reproduce a higher number of example features in their designs. Said fact shows that the participants fixate upon the example features. When presented with additional alternate representations of the design problem, in the Defixation Condition, the expert designers successfully mitigate their fixation. Unfortunately, these defixation materials do not help novice designers.

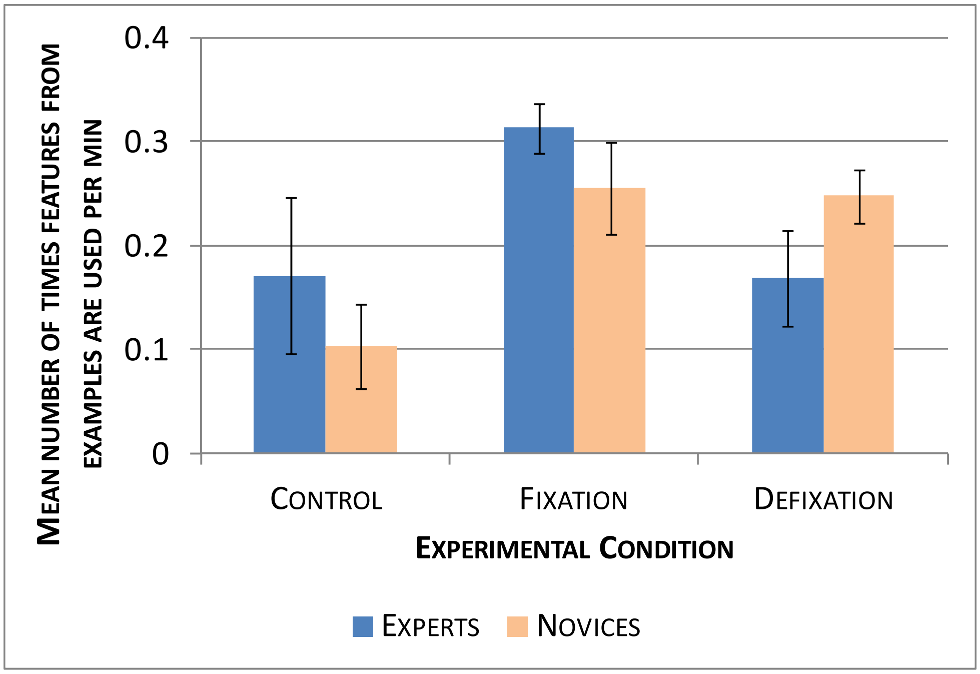


Figure 57: Both expert and novice designers replicate example solution features in their designs to the same extent. Error bars show (±1) standard error.

The one-way ANOVA results show that the mean number of times participants use example solutions, per minute, varies significantly across the experimental conditions (F(5,59) = 2.40, p =0.05). The data are normally distributed and possess homogeneous variance across the conditions. Results of pair-wise a-priori t-tests are available in Table 15.

Table 15: A-priori comparisons for mean number of times participants use example features per minute

Conditions compared	**p**
Comparisons evaluating the hypotheses:	
Expert Fixation – Novice Fixation	0.39
Expert Control – Novice Control	0.36
Expert Defixation – Novice Defixation	0.27
Expert Control – Expert Fixation	0.04*
Novice Control – Novice Fixation	0.04*
Other interesting comparisons:	
Expert Control – Expert Defixation	0.98
Expert Fixation – Expert Defixation	0.04*
Novice Control – Novice Defixation	0.05*
Novice Fixation – Novice Defixation	0.92

* Statistically significant comparisons at $\alpha = 0.05$

The data indicate that the presence of example solutions causes fixation. Both expert and novice participants replicate example features in their solutions. Since many of the features in the example solution are common, the Control Group's solutions will contain them, but the Control Group produces these example features to a limited extent as compared to the participants in the Fixation Condition. It is interesting that the expert control replicates features more often than the novice control does. The data also suggest that the use of defixation materials helps expert designers mitigate, to some extent, their fixation. Conversely, the defixation materials do not help novice designers mitigate their fixation to the example features.

Percentage of Features Used from the Example

The data show that participants across the various experimental conditions implement a different percentage of example solution features in their design, another indication of design fixation. These results are shown in Figure 58. As observed, the participants in the Fixation Condition replicate a higher percentage of example features in their solutions, per minute, as compared to the Control Group. This supports the Fixation Hypothesis. The expert participants mitigate their fixation, to some extent, with the help of alternate representations of the design problem. Still, for novice designers, the defixation materials prove insufficient to alleviate fixation.

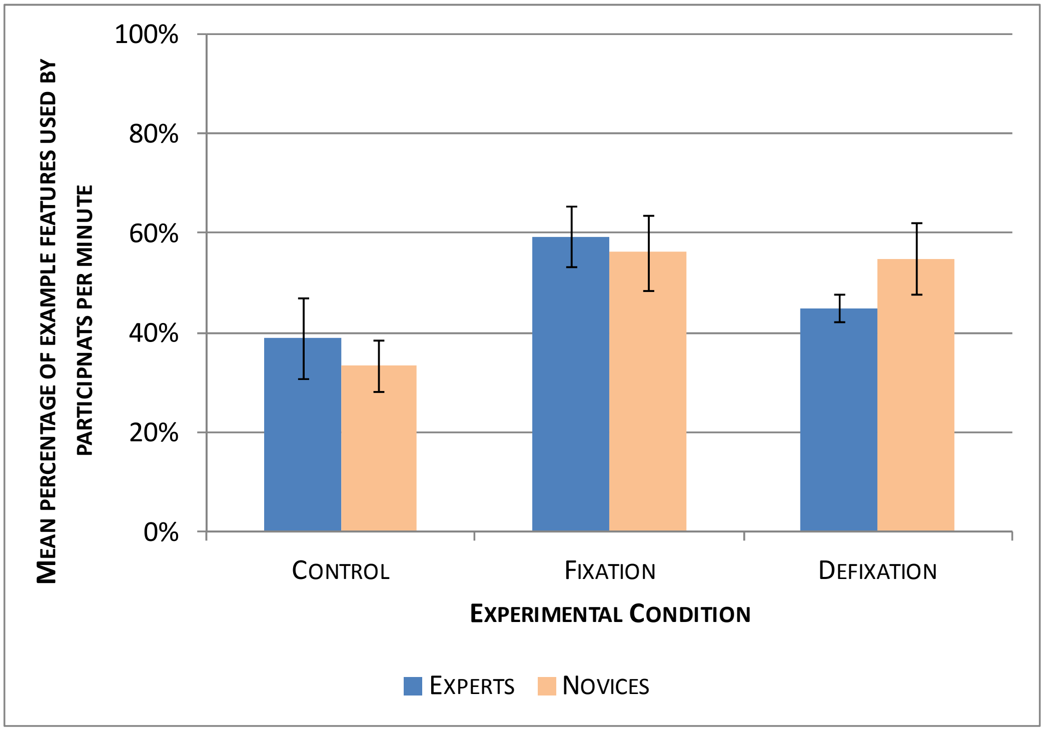


Figure 58: The mean percentage of example features used, per minute, varies significantly across the conditions. Error bars show (±1) standard error.

For statistical analysis, a one-way ANOVA is performed on the data. The data satisfy homogeneity of variance requirements for ANOVA, but are not normally distributed. However, the sample size is large enough to ensure the accuracy of this statistical method. The results reveal a significant variation of the mean percentage of example features used, per minute, across the conditions (F(5,59) = 2.73, p =0.03). Once again, a-priori t-tests are used for pair-wise comparisons. These a-priori comparisons are depicted in Table 16.

Table 16: A-priori comparisons for the mean percentage of example features, per minute, used by participants

Conditions compared	**p**
Comparisons evaluating the hypotheses:	
Expert Fixation – Novice Fixation	0.71
Expert Control – Novice Control	0.55
Expert Defixation – Novice Defixation	0.25
Expert Control – Expert Fixation	0.03*
Novice Control – Novice Fixation	0.02*
Other interesting comparisons:	
Expert Control – Expert Defixation	0.52
Expert Fixation – Expert Defixation	0.09*
Novice Control – Novice Defixation	0.02*
Novice Fixation – Novice Defixation	0.91

* Statistically significant comparisons at $\alpha = 0.1$

Participants in the Fixation Condition replicate higher percentages of example features per minute, indicative of fixation to those features. The lack of any significant difference between experts and novices, in the Fixation Condition, suggests that both groups fixate upon the example features to the same extent. As demonstrated by the reduced percentage of example features utilized by experts in the Defixation Condition, expert designers can mitigate their fixation by using the defixation materials provided to them. Conversely, as evidenced by the absence of any significant difference between the

Fixation and the Defixation conditions, the defixation materials do not help novice designers mitigate fixation.

Number of Energy Sources Used

It is observed that design experts and novices differ considerably, across the conditions, in the use of various energy sources. The mean number of total energy sources, used by the participants across the conditions, is shown in Figure 59. In all the conditions, design experts outperform novices in the total number of energy sources. Moreover, as a result of fixation, the number of energy sources used by experts is relatively low in the Fixation Condition. Still experts overcome this fixation, with the help of the defixation materials, in the Defixation Condition. It is observed that, without the presence of an example showing an energy source, the novices in the Control Condition do not list the energy source powering their ideas. With the example, in both the Fixation and the Defixation conditions, they list energy sources. Even so, the total number of sources is still less than the quantity generated by expert designers.

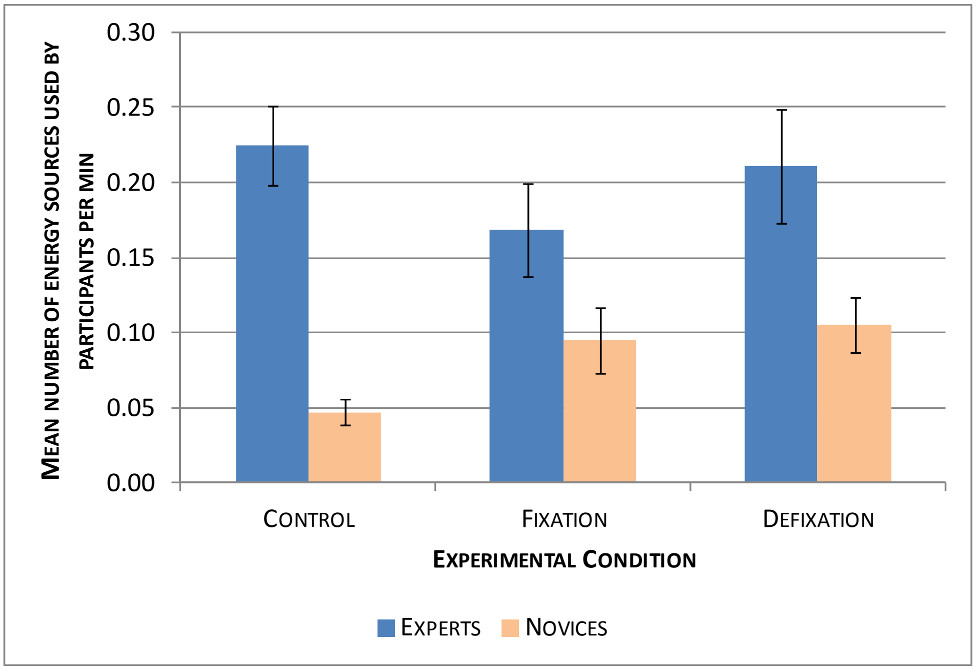


Figure 59: Expert designers use more number of energy sources in their solutions per minute compared to the novices. Error bars show (±1) standard error.

A one-way ANOVA is used statistically analyze the data. It is observed that the mean number of energy sources used by the participants, per minute, varies significantly across the conditions (F(5,59) = 6.59, $p < 0.001$). Pair-wise a-priori comparisons are depicted in Table 17.

Table 17: A-priori comparisons for mean number of energy sources used by the participants per minute

Conditions compared	**p**
Comparisons evaluating the hypotheses:	
Expert Fixation – Novice Fixation	0.05*
Expert Control – Novice Control	<0.001*
Expert Defixation – Novice Defixation	<0.007*
Expert Control – Expert Fixation	0.14
Novice Control – Novice Fixation	0.22
Other interesting comparisons:	
Expert Control – Expert Defixation	0.72
Expert Fixation – Expert Defixation	0.24
Novice Control – Novice Defixation	0.14
Novice Fixation – Novice Defixation	0.79

* Statistically significant comparisons at $\alpha = 0.05$

Evident from an analysis of the statistical data, expert designers utilize, in all conditions, a higher mean number of energy sources, per minute, as compared to novices. This strongly supports the Expertise Hypothesis. Expert designers hold a larger knowledge in their memory, including a greater number of energy sources. Since they produce ideas using their knowledge, they typically outperform novices. Despite this fact, if they are introduced to the example solution, they use less energy sources in their ideas; still, this reduction is statistically insignificant. In the case of novice participants, if they are not introduced to the example solution containing an energy source, they do not list an energy source at all in their solution. Though the introduction of the example precipitates a significant increase in the number of listed energy sources, this increase does not bring the novices up to the level of an expert.

Percentage of Ideas Using Gas Engine

This metric quantifies the fixation of the participants to the energy source specified in the example. Figure 60 shows the mean percentage of participant generated ideas, per minute, involving the gas engine as the power source. As observed in this figure, participants rarely use the gas engine in their solution in the absence of the example solution. Provided with the example solution, they utilize the gas engine as a power source much more extensively. Fortunately, mitigation of the fixation seems to occur via the use of a list of alternate energy sources included within the defixation materials.

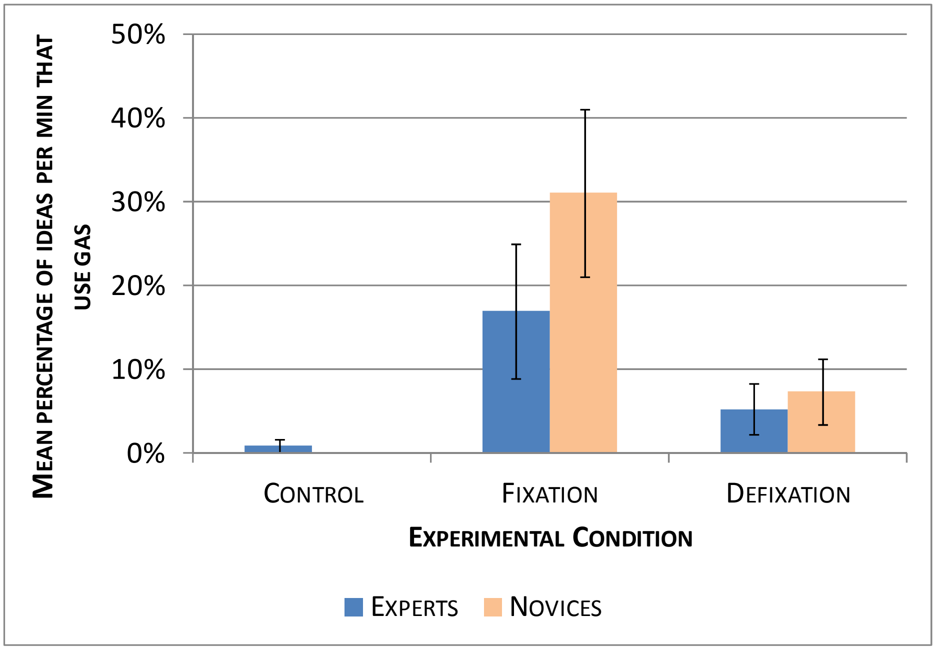


Figure 60: Both design experts and novices tend to fixate upon the energy source specified in the example solution. Error bars show (±1) standard error.

The data does not satisfy the normality and homogeneity of variance requirements for a one-way ANOVA. Thus, a one-way ANOVA with randomization [117, 118] is used for the statistical analysis of the data. The results indicate that the mean percentage of solutions, per minute, using the gas powered engine varies significantly across the experimental conditions (F(5,59) = 25.12, p =0.01). Using pair-wise permutation tests, a-priori comparisons are undertaken, and the results are shown in Table 18.

Table 18: A-priori comparisons for the percentage of solutions per minute that use the gas engine as the power source

Conditions compared	**p**
Comparisons evaluating the hypotheses:	
Expert Fixation – Novice Fixation	0.26
Expert Control – Novice Control	<0.001*
Expert Defixation – Novice Defixation	0.70
Expert Control – Expert Fixation	0.12
Novice Control – Novice Fixation	<0.001*
Other interesting comparisons:	
Expert Control – Expert Defixation	0.24
Expert Fixation – Expert Defixation	0.26
Novice Control – Novice Defixation	<0.001*
Novice Fixation – Novice Defixation	0.04*

* Statistically significant comparisons at $\alpha = 0.05$

These results also provide strong support for the Fixation Hypothesis. As evidenced by the statistical results, both expert and novice participants in the Control Condition generate a relatively low percentage of solutions using the gas engine. Participants tend to use gas engines in their solutions when provided with the example solution. A significant disparity exists between the Control and the Fixation conditions, for novice designers, in the percentages of solutions generated, per minute, using the gas engine as the power source. Even in the case of expert designers, this metric reveals an increase, of relative statistical insignificance, from the Control to the Fixation

Conditions. Both groups successfully mitigate this fixation when provided with alternate representations of the design problem, including a list of potential energy sources.

Discussion

The results provide extremely useful insights regarding the different fixation behaviour of design experts and novices. In fact, the results support the Expertise Hypothesis. One can observe that design experts in all three conditions outperform novices in terms of the quantity of ideas and the total number of energy sources employed in the ideas. This could be due to the larger knowledge accumulated by solving open-ended design problems. In essence, their knowledge is much broader than the novices, perhaps leading them to a wider initial solution space to discover solutions.

The data do not support the Fixation Hypothesis. Experts fixate on the features of the example solution to the same extent as novices. In terms of quantity of ideas, they outperform novices in all the conditions; however, the presence of fixating example causes a significant reduction in their quantity. At the same time, they replicate the example features in their solutions to the same extent as novices. The data also show that when provided with the fixating example, they replicate higher percentage of example features in their solutions. In the presence of example, the number of energy sources used by them shows a significant reduction and number of solutions using gas engine shows an increase. All these results provide strong support to the argument that experts fixate to the same extent as novices.

It is observed that the participants in the Novice Control Group use most of the example features, even without the example solution. Most of the features utilized in the example solution are very common. In other words, they are the first ideas that come to mind when a participant thinks about the solution. This might explain why we do not observe a significant variation in quantity across the novice conditions. The novice participants in the Control Group may fixate to the initial ideas that come to their mind. Coincidentally, said features are directly provided to the other groups.

The results also show a lack of influence of the defixation materials on novices, while they help expert designers in mitigating their fixation to a significant extent. It has been already shown by Linsey et al. [13] that experts make use of the alternate representations provided to them to successfully mitigate their fixation to the example solution. In case of novice designers, there are no significant differences between the Fixation and Defixation Groups in terms of the metrics, except in percentage of gas powered solutions. The Defixation Group powers their solutions with gas engine in significantly lower number of cases. This is an interesting result as they are directly provided with a list of energy sources that they can use. However, the total number of energy sources employed by them does not vary significantly from the Fixation Group. Based on this observation it can be argued that novice designers make use of defixation materials only when said materials provide alternate solutions directly to them.

Overall, the results reinforce the accuracy of conclusions already found in the literature regarding the effects of expertise and the influence of defixation materials for engineers. Purcell and Gero [14] observe that mechanical engineers fixate to examples while industrial designers do not. As stated previously, the current sample is mostly mechanical engineers. Combining the results from this study with the study by Purcell and Gero, it can be argued that domain expertise plays an important role in the effectiveness of various innovation tools, including those used to overcome design fixation. This also highlights the importance of familiarizing our future designers with more diverse examples. These diverse examples can enrich their knowledge and can help them in avoiding their fixation in idea generation when they encounter a new open-ended problem.

Conclusions

Design fixation imposes a significant constraint upon engineering ideation. To increase designer creativity, one must first mitigate fixation effects. The study described in this chapter analyzes the role of expertise in solving open-ended design problems. Building upon the prior study by Linsey et al. [13], a comparison is done on the fixation behavior of design experts and novices. This chapter hypothesizes that that experts' larger knowledge helps them to generate more solutions. This may provide them a wider initial space to look for their ideas and may help to reduce fixation. The results support this hypothesis. At the same time, their larger knowledge does not limit their fixation. Instead they appear to fixate to the same extent as novices but the defixation materials have a more significant effect for experts and almost no impact for novices. These results also have significant implications on the design methods being developed. Many new design methods are initially evaluated with novices. The results from this study clearly indicate that the impact on novices and experts may be very different and some interventions that have little impact for novices will have significant impact for experts.

CHAPTER IX

EFFECT OF REPRESENTATION ON DESIGN FIXATION – THE FIXATION EXPERIMENT WITH PHYSICAL EXAMPLE

The investigations presented in Chapter VIII show that both experts and novices can fixate in the presence of pictorial examples. The effects of examples presented in other formats, especially three-dimensional physical models, are not well understood. In more realistic design situations, the examples from a designer's physical world can influence idea generation. In fact, most of these systems are three-dimensional and can act as idea generation physical examples. The fixation aspects of such examples need to be studied in detail. The difference in the capability of these representations in conveying relevant information also remains unknown. The study presented in this chapter aims to clarify these issues. Based upon the background literature, the following hypothesis is formulated and further investigated in this chapter:

<u>Hypothesis:</u> Designers fixate to both pictorial and physical examples to the same extent.

The following sections present a controlled experiment investigating this hypothesis along with the key results and a discussion of these results.

Method

A between-subject experiment with novice participants was conducted to investigate the hypothesis. This experiment was designed based upon the prior experiments by Linsey et al. [13] and the experiment described in Chapter VIII. Participants generated ideas to solve a design problem in four different groups: No Example Group, Pictorial Example Group, Physical Example Group and Physical Example Defixation Group. In each group, the participants solved the same design problem. The occurrence of example features in their solutions was studied to identify the extent of their fixation to the example.

Design Problem

Similar to the experiment described in Chapter VIII, in this study all the participants solved a "peanut sheller" design problem [13, 91, 115]. Figure 61 shows the design problem statement provided to the participants. This problem asked participants to generate as many ideas as possible for a device that can quickly and efficiently shell peanuts without the use of electricity and with minimum damage to the peanuts. The participants were instructed to generate as many ideas as possible to solve this design problem. None of the participants were familiar with the design problem before the experiment; but they all had experienced the routine task of shelling peanuts.

Design Problem - Device to Shell Peanuts

Problem Description:
In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal 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.

Figure 61: Design problem description provided to the participants

Experiment Groups and Examples

The four experiment groups differed in both the type of additional materials provided and the manner in which the example was presented. The No Example Group received only the design problem statement and no supplemental material. The Pictorial Example Group received an example solution, in the pictorial form, as shown in Figure 62, along with a short description. This pictorial example is same as the one used in Chapter VIII; however, the sketch is redrawn to make it closer to the physical example. The description detailed the operation of the example solution. The exact statement was the following: “This system uses a gas powered press to crush the peanut shell. The shell and peanut then fall into a collection bin”. The Physical Example Group received the same example solution in the form of a physical model (Figure 63). This physical model was not functional; but the participants were not informed of this. They were told that it could function with a gas powered motor. The Physical Example Defixation Group received the same physical model and the defixation materials used in prior experiment described in Chapter VIII (Figure 64). The defixation materials consisted of a brief functional description of the problem along with some back of the envelope calculations, lists of energy sources and analogies that could help solve the problem. These defixation materials were effective in mitigating design fixation in experts , but not in novices.

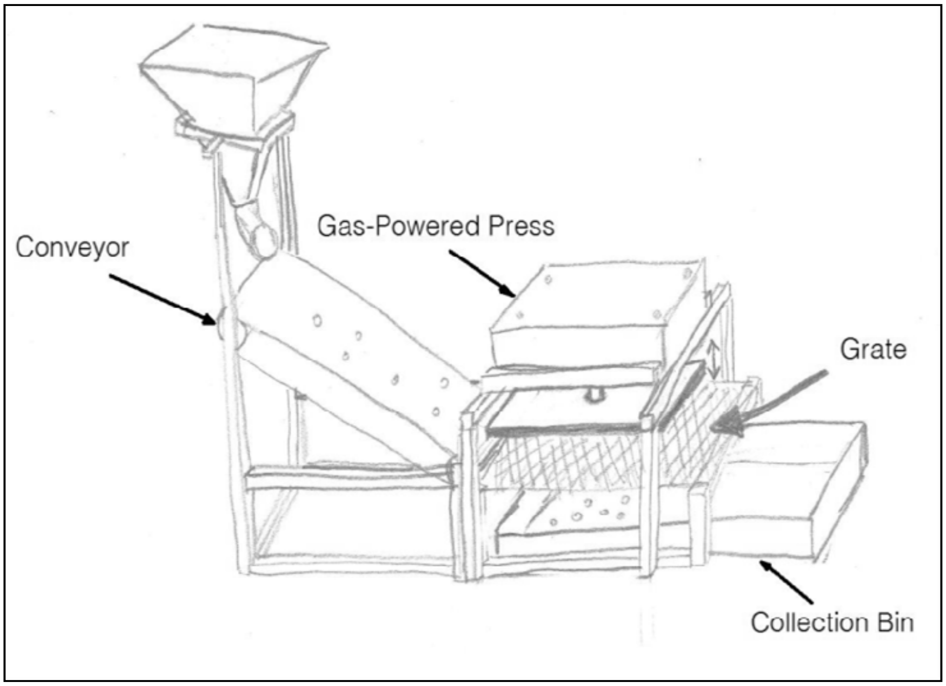


Figure 62: Pictorial example provided to the participants in the Pictorial Example Group

Figure 63: Physical example provided to the Physical Example and Physical Example Defixation groups

Participants

Senior undergraduate and graduate students from Mechanical Engineering Department at Texas A&M University participated in this study. There were a total of 29 participants (21 undergraduate students and 8 graduate students). Six were in the No Example Group, seven in the Pictorial Example Group and eight each in the remaining two groups. The graduate students were equally distributed across the conditions. Six participants were female, and the average age of the participants was 23. None of the participants possessed more than six months of industrial design experience.

To assist you in developing as many designs as possible, consider the following clarification to the problem:

Functions:
- Import natural or human energy to the system
- Convert and transmit energy to peanut
- Remove peanut shell (remove outer structure from inner material)
- Separate removed shell (outer structure) from peanut (inner material)

Example Analogies that You Might Find Helpful:
- Hull
- Shuck
- Husk
- Clean (clean a deer, clean a fish or scale a fish)
- Soak
- Heat, Roast
- Dissolve
- Pod
- Pit, stone
- Burr (deburr something)
- Ream
- Bark (bark a tree)
- Skin
- Pare apples
- Pluck, deplume (strip feathers)
- Peel
- Grind (like a nut grinder)
- Brittle fracture

Natural Energy Sources Available:
- Wind
- Solar
- Running water streams
- Captured rain water at a height
- Solar
- Human
- Animal

Back-of-the-envelope Calculations:

A quick analysis shows that a much greater quantity of power (or force) is needed to act on many peanuts simultaneously compared to applying power to a few peanuts at a time.

Figure 64: Defixation material provided to the participants in the Defixation Group [13]

Procedure

As the participants entered the experiment room, they were directed to their workspaces. Up to four students participated at a time, and their workspaces were separated by dividers. As the experiment began, they received the design problem statement along with the appropriate supplemental materials as determined by their experimental group. They were given five minutes to read and understand the design problem. The participants utilizing the physical example were also allowed to inspect it. The physical model was displayed on a table in front of them. These five minutes were followed by a 45 minute idea generation. They were instructed to generate as many ideas as possible. To encourage their participation, they were told that the participant with greatest number of solutions would receive a prize. To ease logistics, this prize was given to all participants, but the participants did not know this prior to the experiment. The examples were available to the participants throughout the session. The participants were asked to sketch their ideas and supplement those sketches with labels and short descriptions of each part. At the end of the experiment, the participants were asked about their prior exposure to the design problem and any relevant industrial experience.

Metrics for Evaluation

To measure fixation, five metrics, used in the prior experiment described in Chapter VIII, are used: number of repeated example features, percentage of reused example features, quantity of non-redundant ideas, number of ideas for energy sources and percentage of ideas using a gas engine. These metrics are calculated in a similar manner to that explained in Chapter VIII. To ensure reliability, a second independent reviewer blind to the experimental conditions analyzes 52% of the data. The obtained inter-rater agreements (Pearson's correlation) are high (0.95 for number of example features, 0.86 for percentage of features reused from example, 0.87 for quantity of non-redundant ideas, 0.88 for number of energy sources and 0.89 for percentage of solutions using gas powered engine), indicating that these metrics are reliable [92].

Results

This section outlines the results obtained for various metrics used in the current study. The solutions generated by the participants are broken down with the help of a functional basis and the various metrics for each group are determined. A detailed description and discussion on the results follow in the following subsections.

Number of Repeated Example Features and Percentage of Reused Example Features

The results from the number of repeated example features and the percentage of reused example features indicate that the three groups with examples fixate to the example features (Figure 65 and Figure 66). Compared to the No Example Group, all other groups replicate more example features. Since the example contains common solutions to the requisite functions, the No Example Group utilizes some example features in their ideas. Still, the level of utilization is relatively small compared to the other groups. A one-way ANOVA indicates that the mean number of repeated example features varies significantly across the conditions ($F(4,25) = 3.38$, $p<0.03$). Pair-wise a-priori comparisons show that the No Example Group generates significantly fewer example features compared to all other groups (No Example vs. Pictorial Example: $p<0.08$; No Example vs. Physical Example: $p<0.001$; No Example vs. Physical Defixation: $p<0.04$). As expected, all other pair-wise comparisons are not statistically significant. The percentage of reused example features follows the same trend (Figure 66). Across the conditions, the data shows an overall significant difference (using one-way ANOVA: $F(4,25) = 5.92$, $p<0.001$); moreover, a lower percentage exists in the No Example Group as compared to the other groups (No Example vs. Pictorial Example: $p<0.001$; No Example vs. Physical Example: $p<0.001$; No Example vs. Physical Defixation: $p<0.01$).

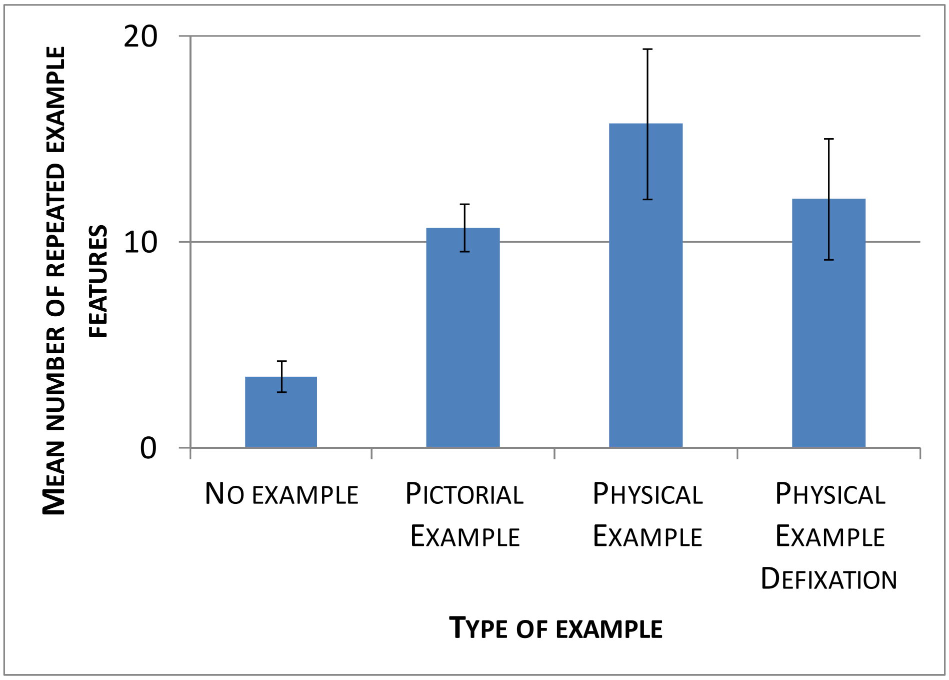


Figure 65: Variation of mean number of repeated example features across the experiment groups. Error bars show (±1) standard error.

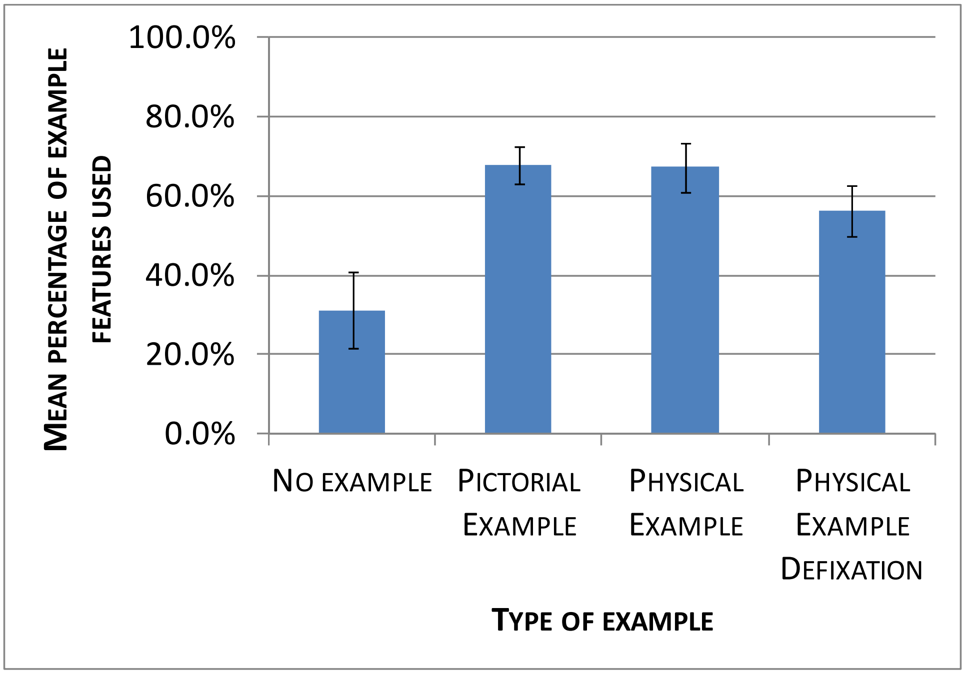


Figure 66: Variation of mean percentage of example features used across the groups. Error bars show (±)1 standard error.

These results strongly support the hypothesis. Examples in both the pictorial and the physical model formats fixate participants. The mean number of repeated example features is slightly higher for the Physical Example Group as compared to the Pictorial Example Group, but this difference is statistically insignificant. Interestingly, the defixation materials do not help novice participants mitigate their fixation. These results are consistent with the prior studies. Linsey et al. [13] show that expert designers successfully mitigate their fixation to pictorial examples; but a follow-up study described in Chapter VIII shows that these materials are not effective for novice designers.

Quantity of Non-redundant Ideas

The quantity of non-redundant ideas varies across the four groups (Figure 67). A one-way ANOVA shows statistically significant variation of this metric across the groups (F(3, 25) = 2.41, $p<0.09$). Pair-wise a-priori comparisons show that the Pictorial Example Group produces significantly less ideas than the other groups (Pictorial Example vs. No Example: $p <0.09$; Pictorial Example vs. Physical Example: $p< 0.02$; Pictorial Example vs. Physical Example Defixation: $p< 0.05$). Other pair-wise comparisons are statistically insignificant.

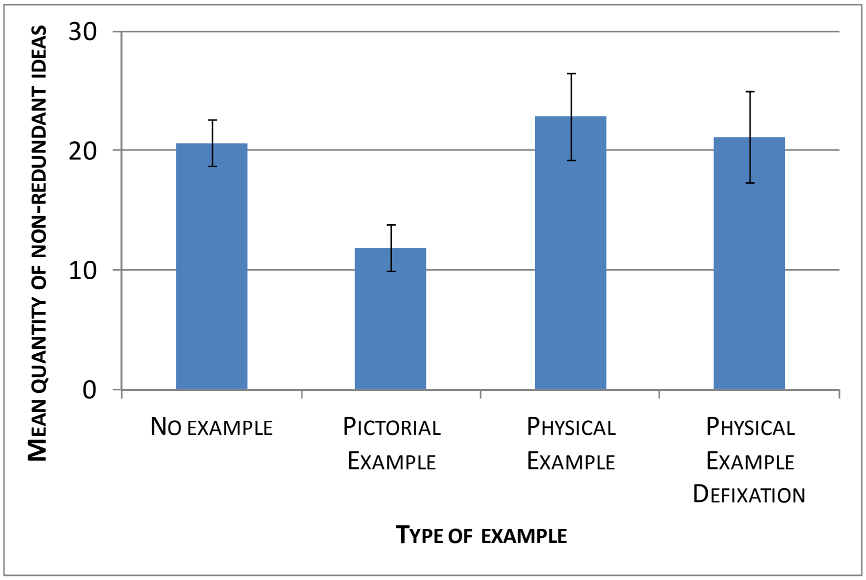


Figure 67: Variation of mean quantity of non-redundant ideas across the experiment groups. Error bars show (±)1 standard error.

These results highlight extremely interesting trends in the data. As expected, participants with the pictorial example generate a lower quantity of novel ideas, an indication of fixation. Conversely, the Physical Example Group does not follow this pattern. In fact, they generate the same mean quantity of non-redundant ideas as the No Example Group. This indicates that, though the Physical Example Group replicates many example features in their solutions, they can generate a greater quantity of novel ideas than the Pictorial Example Group. The Physical Example Defixation Group does not show any improvement in the mean quantity of non-redundant ideas. Said fact indicates that the defixation materials do not significantly help the participants. Additionally, the data seems to reveal that, though the Physical Example Group does repeat features from the example, said fixation does not appear to limit their ability to generate a high quantity of ideas. Contrasting this with prior studies measuring design fixation [12, 14, 25], it is essential to consider quantity of ideas as a measure for fixation, in order to get a complete picture.

Energy Sources Fixation

The mean number of energy sources and the mean percentage of solutions using gas as the power source do not vary much across the conditions (Figure 68 and Figure 69). A one-way ANOVA indicates that both metrics do not significantly vary across the conditions (Number of energy sources: $F(4,25) = 1.42$, $p = 0.26$; Percentage of solutions with gas powered press: $F(4,25) = 0.21$, $p = 0.88$). Still, the Pictorial Example Group produces a lower mean number of energy source ideas as compared to other groups. Said result is consistent with the prior study discussed in Chapter VIII.

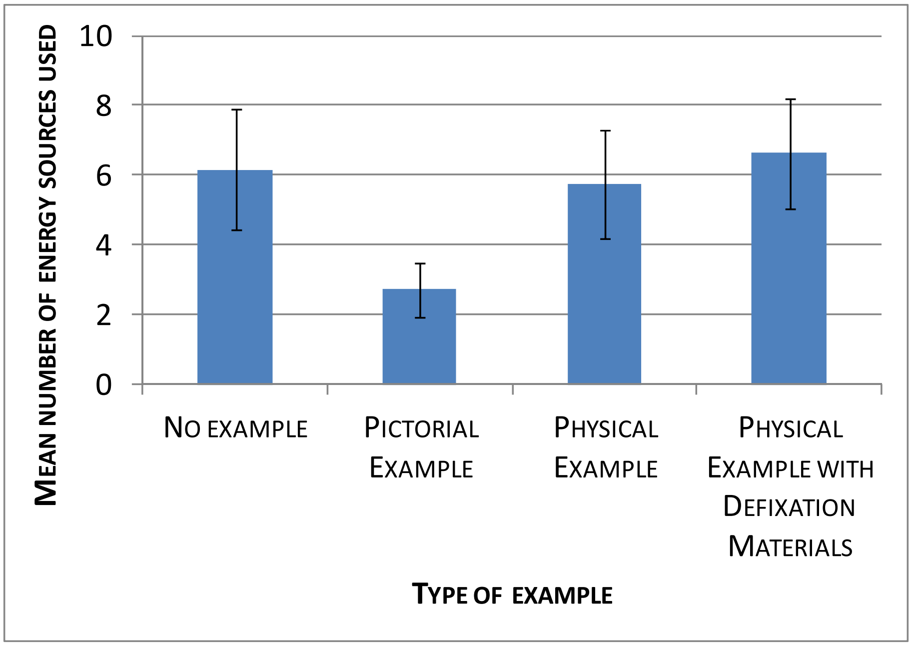


Figure 68: The variation of the mean number of energy sources across the experiment groups. Error bars show (±) 1 standard error.

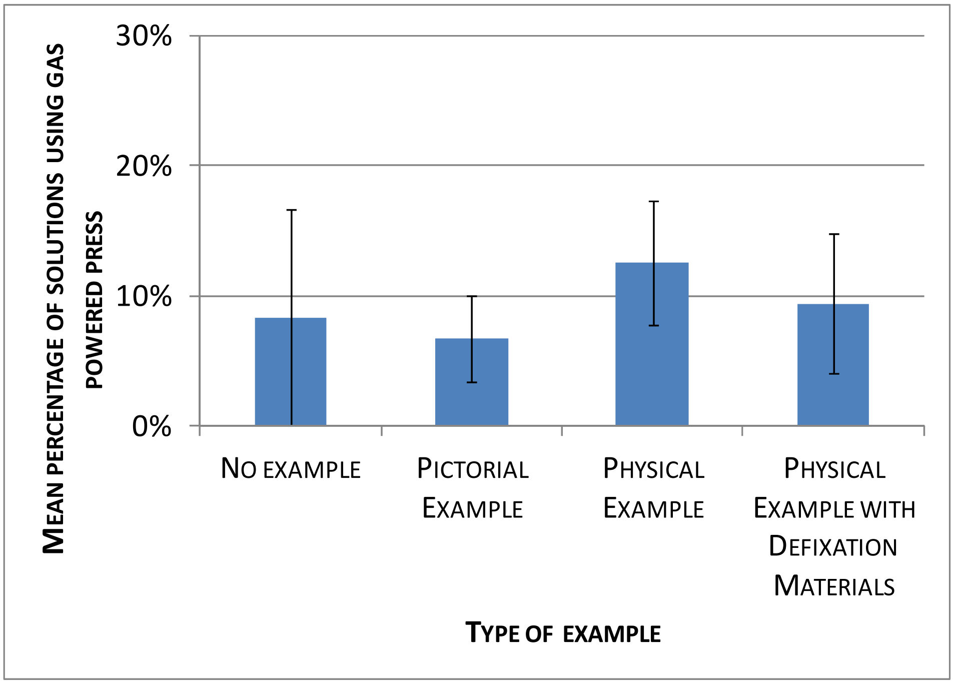


Figure 69: Variation of the percentage of solutions using a gas engine across the experiment groups. Error bars show (±) 1 standard error.

Consistent with prior studies, the Pictorial Example Group produced a lower mean number of ideas for energy sources. The Physical Example Group produced the same mean number of ideas for energy sources as the No Example Group, indicating no fixation. In this study as well, defixation materials did not have any effect on novice designers. Interestingly, the percentage of solutions using a gas powered press remains constant across all the conditions.

Discussion

The results indicate that the participants fixate to features of the pictorial example. They replicate many features from the example in their solutions resulting in a higher mean number of repeated example features as compared to the No Example Group. The Pictorial Example Group produces less energy source ideas as compared to other groups; still, the percentage of solutions utilizing a gas engine remains constant across the conditions. These results are consistent with prior studies which demonstrate that designers fixate to pictorial examples [12-14, 25].

Participants utilizing physical examples fixate to the example solution features to the same extent as those utilizing the pictorial example. This result strongly supports the hypothesis. Also, the Physical Example Group produces significantly more non-redundant ideas as compared to the Pictorial Example Group. In fact, the quantity is comparable to that of the No Example Group. The mean number of solutions remains the same across all the conditions. Said observation indicates that, for a given solution, the Physical Example Group produces more ideas satisfying the requisite functions. In the No Example and the Pictorial Example groups, participants generate many partial solutions which satisfy only some of the necessary functions of the peanut sheller (for example: a solution contains ideas to only shell peanuts but does not include ways to separate the broken shells). Though some of the ideas are replicated from the example, the Physical Example Group tends to produce a greater quantity of complete solutions. The presence of fixation is not observed in the use of energy sources in solutions. These results possess extremely important implications for engineering design. More specifically, the results indicate that, though examples in the form of physical models can lead to design fixation, they can also lead designers to more complete solutions. The presence of a physical model during idea generation might lead designers to consider each feature of the model and subsequently generate solutions for the function each example feature fulfils. Pictorial examples containing the same amount of information fail to have the same effect. This indicates designers might derive different magnitudes of information from these two types of examples. As a consequence, physical representations might play an important role in the design process because designers might extract a greater amount of information from them.

As explained in the previous chapters, existing literature provides conflicting guidelines concerning fixation caused by the building of physical models during engineering idea generation. Kiriyama and Yamamoto [15] observe that novice designers building physical models during idea generation fixate to variations of their initial ideas. A similar observation is made by Christensen and Schunn [35] in their study on practicing designers. The Paperclip Experiment, with a simple design problem, fails to detect fixation from working with physical models. In a follow-up controlled study (Sunk Cost Experiment), shows that the design fixation observed in prior studies occur because of the Sunk Cost Effect; in other words, fixation is not an inherent part of the building process. The Sunk Cost Effect entails an adherence to a chosen course of action after significant investment is devoted to that path [41, 47]. During idea generation, if designers spend a large amount of time, money or effort solving design problems, they tend to fixate to variations of their initial ideas. When designers build their own physical models, they fixate as demonstrated by the prior studies [15, 35]. In this study, designers do not fixate to the physical example any more than to the pictorial one because they receive the physical model, and the sunk cost associated with building is low. Similar results are reported by Youmans in a recent study [16]. These results reinforce the argument that the Sunk Cost Effect is a major factor in causing design fixation.

The results also show that the defixation materials do not help novice designers mitigate their fixation to example solutions. This result also validates the results of the Fixation Experiment explained in Chapter VIII, which shows that the same defixation materials do not help novice designers mitigate their fixation to pictorial examples. Linsey et al. [13] show that expert designer can use the resources provided to them, in the form of defixation materials, and significantly mitigate their fixation to the example features. Unfortunately, novice designers fail to utilize these materials in either pictorial or physical form.

Conclusions

This chapter investigates the effects of physical examples on design fixation. The study presented hypothesizes that designers fixate to physical examples to the same extent as to pictorial. A between-subject controlled experiment evaluates this hypothesis. In the experiment, participants generate ideas for a design problem with the help of either pictorial or physical examples. The occurrence of example features in their solutions is studied to identify fixation. The results support the hypothesis. The participants fixate to physical examples to the same extent as to pictorial examples. Still, participants with physical examples generate a greater quantity of complete solutions. These results also strongly support the argument that, during idea generation, design fixation is caused by the Sunk Cost Effect and fixation is not an inherent aspect of working with physical models. Due to these reasons, quick prototyping techniques such as rapid prototyping need to be encouraged during engineering design. Designers can also employ separate technicians to build prototypes of their ideas. Said strategy might reduce the Sunk Cost Effect and resultantly lead to a greater quantity of novel ideas.

CHAPTER X

CONCLUSIONS AND FUTURE WORK

Physical models are potential tools that can help designers in the generation of novel and functional ideas during their idea generation. Unfortunately, their effects on design cognition have not been subjected to vigorous research. The guidelines available from current literature are conflicting. In order to provide clarity regarding the role of physical models, a series of studies are conducted as outlined in this thesis. Based on the insights from these studies, a set of guidelines are formulated that can assist designers in the implementation of physical models. A design method is also formulated to improve the efficiency of physical modeling. The following sections detail the insights gained from the various studies in this thesis along with brief summaries of the experiments. Future work related to physical models and various other areas of engineering design are also presented.

Conclusions: Physical Models in Engineering Idea Generation

The series of experiments described in the previous chapters provide very interesting and important insights about the use of physical models as idea generation tools. From the Paperclip Experiment and the Sunk Cost Experiment, it is clear that physical models supplement designers' erroneous mental models. This leads them to the generation of a higher percentage of ideas satisfying the problem requirements. This result highlights the importance of promoting the use of physical models as idea generation tools. Further, the results from the Paperclip Experiment and the Sunk Cost Experiment together show that design fixation is not inherent with the building of physical models. Conversely, the Sunk Cost Effect affects the presence of design fixation in physical modelling. Hence fixation associated with physical modelling can be mitigated to some extent by reducing the cost (in terms of money, time or effort) associated with building. Quick prototyping techniques can be very helpful in the reduction of the associated cost and hence design fixation. Another potential solution is to separate the building process from idea generation and employ a second person to build the models as the designer concentrate on the generation of ideas. The Qualitative Study verified these findings in more realistic settings. Overall, these three studies together demonstrated that lower cost physical modelling techniques can be highly beneficial in engineering idea generation by increasing the number of functional designs.

The Stunt Car Experiment revealed another interesting aspect of physical models: their ability to mitigate design fixation to undesirable features in an example solution. Designers use various examples from their surroundings to aid their idea generation. However, they tend to fixate to various features in those examples as shown by numerous prior studies in design and Psychology [12-14, 25, 107]. This type of fixation to undesirable features can challenge the functionality of the idea itself. It is observed that as designers build and test the physical models of their ideas, they obtain instant feedback regarding the drawbacks of such features. This leads them to change those features and thus mitigate the fixation to those undesirable features. This strategy of learning through their own mistakes can be very powerful in training our future designers and opportunities for practicing engineers to be lifelong learners.

Conclusions: Design Fixation to Examples

The two fixation experiments described in this thesis investigate the effects of expertise and representation of examples in design fixation to presented examples. The first experiment replicates the experiment conditions of the experiment with design faculty by Linsey et al [13] with novice participants and compares the data obtained with those from design faculty. The results show that both design experts and novices fixate to the examples by the same extent. However the fixation in experts can be easily mitigated with the help of additional information provided to them including a list of analogies, energy sources and some back of the envelope calculations. However, with the available sample, the defixation materials did not show any effect on novices. Further, the effect of type of representation used to convey the example to the designers is studied. The participants are provided with a pictorial example or a physical example, depending on their experiment condition. It is observed that the pictorial example and physical example fixate designers to the same extent; however, physical example leads them to concepts satisfying more functions in the functional basis. These results demonstrate that there are many factors like the expertise level of designers and the type of representations they use affect design fixation. Hence design fixation needs a more detailed investigation in future.

Conclusions: Model Error Reduction Method

The Model Error Reduction Method is developed and tested based on the insights from the studies mentioned above. It is clear that building physical models with lower associated cost is more advantageous and many times errors during physical modelling lead to higher associated cost. The common error committed by designers during physical modelling in graduate design projects are identified through content analysis of the reports from the teams and through specialized templates. A set of guidelines is developed for mitigating these issues. Further to aid designers in avoiding two most critical issues, a Model Error Reduction Method is formulated. The two issues that the method address are: failure to include all critical forces in the design of the system and failure to design connections of parts within the system. A controlled experiment is conducted to evaluate the usefulness of the Model Error Reduction Method. The results show that the method is effective in helping designers in the identification of missing critical loads and contact forces. Hence it can be concluded that the Model Error Reduction Method is a strong candidate for inclusion in the building of physical models.

Future Work

The research described in this thesis has answered many questions regarding the effects of physical models on design cognition, meanwhile uncovering many directions for future research. The results from this research show that physical models are potential tools that can help designers in the generation of very novel and functional ideas. However, as the area of physical models is very rich and comparatively less studied, it requires further exploration. The design method presented here mitigates two potential issues that designers face during physical modelling. More methods are required to make that process more effective. The subsections below detail the future work in the area of physical models and the related topics.

Future Work on Physical Models

An open question in the area of concept generation with physical models is the role of throw-away prototypes. The advantages of using specific kinds of prototypes at different stages of product development are yet to be clarified. If designers spend more time on a single prototype, they get fixated to that idea and generate variations of that henceforth. Throw-away prototyping can be useful in such cases. Various materials and tools are easily available to support this kind of prototyping. These easy-to–build prototypes can support innovation; whereas, more complicated prototypes can be used to reduce the risks associated with innovation. Complicated prototypes can be built to understand the flaws in the design and eliminate them before they cause further costs in production. The type of prototype suitable for each stage of design needs to be identified and their uses need to be clarified.

Another interesting direction of research will be the development of guidelines for choosing the specific materials and processes to be used for physical modeling according to the situation in hand. Currently, no such guidelines exist in the literature. Developing such a set of guidelines can be very useful for designers, especially for novices with limited exposure to physical modelling. Ideally, a computer-assisted system that suggests some prototyping methods and materials based on the requirements from the model needs to be developed.

The Model Error Reduction Method introduced in Chapter VII targets to mitigate the two critical issues that designers face during building of physical models. The preliminary testing with the help of a controlled experiment shows that this method is effective. However, a testing in more detailed manner in actual project situations is needed to affirm this result further. This method can be implemented as a part of the senior design or graduate design curriculum and the results in the physical modelling stage can be studied. Further, similar design methods need to be developed to solve the other critical issues mentioned in Chapter VII.

Another intriguing issue that engineers face is their lack of planning during the building process. This is a major issue when there are strict restrictions on the money and time one can spend on the design process. Designers generally use planning methods like Gantt charts. These do not account for any unexpected reallocation during the building process, as the building process reveals the flaws in their ideas. In many cases, they finish their prototypes prematurely, as the available resources run out. Sometimes, this forces designers to leave their ideas. This inefficient allocation of resources leads to their wastage, without fulfilling the goals. It will be useful to develop a method which forces designers to plan properly at the beginning of the building process.

Similarly, the effect of scale of physical models on the ideas generated needs to be studied. In the Sunk Cost Experiment, the participants who build their ideas using plastic, scale majority of their ideas up, in order to make the building feasible. It will be interesting to investigate if scaling of ideas has any effect on the ideas generated. If there is any effect due to this factor, the results obtained in the Sunk Cost Experiment can be partially caused by the scale difference.

Future Work on Sunk Cost Effect

The results from the current research have shown that Sunk Cost Effect is a critical factor in engineering idea generation. However, the Sunk Cost Experiment investigates the effect of cost in terms of time spent building physical models while the other two factors in sunk cost (effort and money) are controlled. In more realistic situations, all these three factors can vary together, making sunk cost difficult to interpret. For example, building with a low cost material can be more time consuming. In such cases, the effect of these individual factors on sunk cost and on idea generation may not be straight forward. More work is needed in this area to understand the effects of these individual factors and then a utility model for sunk cost needs to be formed in order to completely understand its effect on idea generation.

Future Work on Fixation Experiments

The fixation experiments described in this thesis have shown that the defixation materials for design experts are not very useful for novices. Design fixation being a crucial concern in engineering idea generation, it is essential to develop defixation materials and tactics for designers at various levels of expertise. It will be interesting to see the extent of design fixation when the designers are explained about the reason for some example feature being undesirable. From the Stunt Car Experiment, it is observed that asking novices not to use certain example features does not help in mitigating fixation to those features. This can be largely due to the curiosity of novice designers about those features. If they are explained why those features should not be used, it may help in the mitigation of design fixation.

Another area of interest will be the extent of design fixation in practising professional designers in similar conditions. Most of the research in the area of engineering idea generation using novices target to develop design methods and guidelines that are useful for practising designers. Hence it is important to understand how the idea generation and design fixation of design experts vary from those of novices. Based on this comparison, the design methods being developed currently may not provide the same results for experts as with novices.

Problem Complexity on Idea Generation

Engineering idea generation is a very complex process and involves many factors that can influence the results. Problem complexity can be one of those factors. There is relatively no work done investigating the effect of problem complexity on the quality and quantity of ideas generated. If designers can generate higher quality ideas while solving simpler problems, it may be beneficial to split complex problems to multiple simple problems. Designers can generate higher quality solutions for these simple problems and then these solutions can be combined to form final ideas for the overall problem. The feasibility and benefits of such an approach needs to be investigated. This split-and-solve approach can be helpful for the recent efforts to develop computer-aided tools for idea generation. Using this approach, the complex problems can be viewed as a combination of multiple problems for which solutions exist and can be easily retrieved.

Design of Interfaces

Interface design is another wide open field. In practice, designers often miss interfaces between critical components, which lead to failure of assemblies. In many cases, novice designers develop infeasible interfaces, which wastes their effort. There is no specific method available in existing literature to avoid this problem. Designers need to think about the interfaces when they develop their ideas. They also need to be aware of the manufacturability of interfaces. When they think about functions and components satisfying those functions, they need to think about interfaces too. A method needs to be developed that aids designers in designing the interfaces.

User Interfaces of Products

Another interesting area is the design of user interfaces for innovative products. A previous study has shown that novel products which take care of the user interactions succeed more often that the ones with additional functions [119]. There are many methods existing to design innovative products based on functions. None of them address the user interactions. Providing a method to designers to explore this area can improve user interactions and also help them develop more commercially innovative products.

Metrics for Evaluating Ideas

Finally, the metrics that are currently in use to measure the effectiveness of idea generation need continual improvement. The novelty and variety metrics used in this thesis are not the best metrics to measure the extent of design fixation in those studies due to many reasons. For a simple problem like paperclip problem, where many ideas are generated in the given amount of time, the calculation of novelty and variety measures are difficult and time consuming. Still these measures are used in the current study due to unavailability of better measures. Again, these measures are relative and are not useful in comparing ideas in a treatment condition with those from a controlled condition. These drawbacks points to the necessity of developing an absolute measure to judge ideation effectiveness.

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APPENDIX A

EXPERIMENT MATERIALS AND DATA FROM THE PAPERCLIP EXPERIMENT

1. Experimenter Script – Sketching Only Condition

(Some of the instructions are recorded and played from a computer)

Check list:

- Paper to sketch – Taped down to the table
- Computer of the experimenter – Connected to the projector, playlist of instructions and the training loaded
- Speakers
- Projector – with remote control
- Multicolored pens
- Box of prototyping materials
- Participant consent forms
- Print out of the problem description – taped down and covered.
- Survey
- Stop watch
- Numbered address labels
- Press
- Steel wire pieces – 9” long
- Blank sheet for demo
- Time recording sheet
- Print outs of pictures of paperclips
- Box on the table to keep the watches, pens and mobiles
- 10 sheets of blank sheets for testing

1. Consent

On the table:

- Participant consent forms
- BLACK pen
- Taped down paper
- Design problem taped down and covered.

- Projector on

When participants come, show them the work place.

Start stop watch.

"Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. So, please keep your watches and cell phones in your back pack or the box on this table "(Show the box). **"Also please don't use your pens to sketch."**

Check to make sure that the participants have no mobiles or watches with them.

"You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

You will be asked to complete a series of tasks. You will be asked to generate ideas for a design problem with a short survey at the end of the experiment. The study will require approximately 3 hours. Please let me know if you have any questions about the experiment."

Wait until all of the participants have finished reading to proceed with the experiment. Then say**, "If you agree to participate please sign the form and keep the second copy for your records."**

Wait for participants to sign the consent forms

Collect the consent forms.

"Please put away your copy of the consent forms."

This experiment has multiple activities and all three hours will be required. Your effort will be compensated with extra credits for your design class. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after May 1, 2010 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

Record the questions and answers in case of any.

Answer the questions if any.

2. *Design problem - Sketching*

Uncover the design problem on the table.

"OK, now we are beginning with the experiment. As I already mentioned to you this is based on engineering idea generation process. You are going to create solutions for a real life problem. Please listen to the recorded instructions now."

Play file 1.

At the end of playback "**Are there any questions?"**

Answer if any.

"OK, you may start the idea generation process."

After 15, 20, 30, 40 …. Min "I will exchange your pens now"…. Exchange with next pen

****** BREAK 1.00 hr ********* "**You will have a 5 min break now. Restrooms are outside and there is a water fountain right across the corner. Please be back on time**"

After 1 hr 45 min, **"Please stop the activity"**

****** BREAK 1.00 hr 45 min ********* "**You will have another 5 min break now**"

3. *Design problem – Building*

On the table

- Box of prototyping materials
- PINK sketch pen

Remove

- PURPLE pen

"Welcome back. As a part of the experiment, now you are going to build physical prototypes of your ideas. For helping you in this we have a recorded training for you. I will start the training now."

Play training demo.

Play file 2.

"Are there any questions?"

Answer the questions if any.

You may start now.

After 2 hr 10 min “I will exchange your pens now”…. Exchange with RED (sketch) pen

After, 2 hr 20 min, **“Please stop the activity”**

4. *Testing*

Add to the table

- 10 sheets of paper
- BERRY sketch pen
- Address labels

Remove

- The current sketch pen

Play file 3 in the play list.

Answer the questions if any.

“You may begin now”

After 2 hr 30 min… **“Please stop the activity”**

5. *Paper clips seen*

Add to the table

- BROWN sketch pen

Remove

- BERRY sketch pen

Play file 4 in the play list.

“You may begin now.”

After 2 hr 35 min **“Please stop the activity”**

Switch off speakers

6. *Sketching vs Building time*

Add to the table

- Pencil
- Printouts of the paperclip pictures

Remove

- BROWN sketch pen

"The purpose of the next activity is to measure your skill in sketching and building. For this purpose, please sketch the wire paper clip shown on the paper in front of you, as quickly and accurately as possible. Please use a fresh box for drawing the clips. The time required will be measured. Please raise your hand when you finish the activity. Are there any questions?"

Answer the questions if any.

"You may begin now. " Start stop watch

When participant raise hand, record the time

"Now we are going to measure your building skill. For that, please make the prototype of the paper clip that you have drawn just now, as quickly and accurately as possible, using the tools and steel wire provided to you. The time required will be measured. Please raise your hand once you are done. Are there any questions?"

Answer the questions if any.

"You may begin now."

When participant raise hand, record the time

"Please sketch the wire paper clip shown on paper in front of you. Remember, we are measuring your sketching skill again, so try to do it as quickly and accurately as possible. Please use a fresh box for drawing the clips. The time required will be measured. Please raise your hand when you finish the activity. You may start now."

When participant raise hand, record the time

"Finally, we are going to measure your building skill again. So please make the prototype of the paper clip you have just drawn, as quickly and accurately as possible, using the tools and steel wire provided to you. The time required will be measured. Please raise your hand once you are done. You may start now."

When participant raise hand, record the time

7. *Survey*

Add to the table

- Survey
- Pen

Remove

- Pencil

“This is the final part of the experiment. Please fill out the given survey”

Collect the surveys when finished.

8. *Disbursement*

“You may take the steel wire and the instruments home and build the ideas you already generated. You will have up to a week time to return them. If you return your ideas built, that will be considered as superior effort and you will be given additional extra credit in your design class. This is fully voluntary.

Thank you for your participation and I will make sure that you will receive your extra credit. This concludes your portion of the study. Please remember to not discuss this study with your classmates until after May 1, 2010 since this will bias the data. If you have any questions about this study I can answer them at this time. “

Collect the e-mail id of the participant. At the end scan the drawing sheet and send them.

2. Experimenter Script – Building Condition
(Some of the instructions are recorded and played from a computer)

Check list:

- ○ Paper to sketch – Taped down to the table
- ○ Computer of the experimenter – Connected to the projector, playlist of instructions and the training loaded
- ○ Speakers
- ○ Projector – with remote control
- ○ Multicolored pens
- ○ Box of prototyping materials
- ○ Participant consent forms
- ○ Print out of the problem description – taped down and covered.
- ○ Survey
- ○ Stop watch
- ○ Numbered address labels
- ○ Press
- ○ Steel wire pieces – 9" long
- ○ Blank sheet for demo
- ○ Time recording sheet
- ○ Print outs of pictures of paperclips
- ○ Box on the table to keep the watches, pens and mobiles
- ○ 10 sheets of blank sheets for testing

9. Consent

On the table:

- Participant consent forms
- BLACK pen
- Taped down paper
- Design problem taped down and covered.
- Projector on

When participants come, show them the work place.

Start stop watch.

"Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. So, please keep your watches and cell phones in your back pack or the box on this table "(Show the box). **"Also please don't use your pens to sketch."**

Check to make sure that the participants have no mobiles or watches with them.

"You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

You will be asked to complete a series of tasks. You will be asked to generate ideas for a design problem with a short survey at the end of the experiment. The study will require approximately 3 hours. Please let me know if you have any questions about the experiment."

Wait until all of the participants have finished reading to proceed with the experiment. Then say**, "If you agree to participate please sign the form and keep the second copy for your records."**

Wait for participants to sign the consent forms

Collect the consent forms.

"Please put away your copy of the consent forms."

This experiment has multiple activities and all three hours will be required. Your effort will be compensated with extra credits for your design class. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after May 1, 2010 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

Record the questions and answers in case of any.

Answer the questions if any.

10. Design problem - Building

Uncover the design problem on the table.

"OK, now we are beginning with the experiment. In this experiment, you are required to build the prototypes of your ideas using steel wire. For helping you in this, we have a recorded training for you. Please look at the projection."

Play Training.

Play file 1.

"**Are there any questions?"**

Answer if any.

“OK, you may start the idea generation process.”

After 15, 20, 30, 40 …. Min “I will exchange your pens now”…. Exchange with next pen

(Refer color chart for the order of pens)

****** BREAK 1.00 hr ********* “**You will have a 5 min break now. Restrooms are outside and there is a water fountain right across the corner. Please be back on time**”

****** BREAK 2.00 hrs ********* “**You will have another 5 min break now. Please be back on time**”

After 2 hr 20 min, **“Please stop the activity”**

****** BREAK 1.00 hr 45 min ********* “**You will have another 5 min break now**”

11. <u>Testing</u>

Add to the table

- 10 sheets of paper
- BERRY sketch pen
- Address labels

Remove

- The current sketch pen

Play file 3 in the play list.

Answer the questions if any.

“You may begin now”

After 2 hr 30 min… **“Please stop the activity”**

12. <u>Paper clips seen</u>

Add to the table

- BROWN sketch pen

Remove

- BERRY sketch pen

Play file 4 in the play list.

"You may begin now."

After 2 hr 35 min **"Please stop the activity"**

Switch off speakers

13. *Sketching vs Building time*

Add to the table

- Pencil
- Printouts of the paperclip pictures

Remove

- BROWN sketch pen

"The purpose of the next activity is to measure your skill in sketching and building. For this purpose, please sketch the wire paper clip shown on the paper in front of you, as quickly and accurately as possible. Please use a fresh box for drawing the clips. The time required will be measured. Please raise your hand when you finish the activity. Are there any questions?"

Answer the questions if any.

"You may begin now. " Start stop watch

When participant raise hand, record the time

"Now we are going to measure your building skill. For that, please make the prototype of the paper clip that you have drawn just now, as quickly and accurately as possible, using the tools and steel wire provided to you. The time required will be measured. Please raise your hand once you are done. Are there any questions?"

Answer the questions if any.

"You may begin now."

When participant raise hand, record the time

"Please sketch the wire paper clip shown on paper in front of you. Remember, we are measuring your sketching skill again, so try to do it as quickly and accurately as possible. Please use a fresh box for drawing the clips. The time required will be measured. Please raise your hand when you finish the activity. You may start now."

When participant raise hand, record the time

"Finally, we are going to measure your building skill again. So please make the prototype of the paper clip you have just drawn, as quickly and accurately as possible, using the tools and steel wire provided to you. The time required will be measured. Please raise your hand once you are done. You may start now."

When participant raise hand, record the time

14. Survey

Add to the table

- Survey
- Pen

Remove

- Pencil

"This is the final part of the experiment. Please fill out the given survey"

Collect the surveys when finished.

15. Disbursement

"You may take the steel wire and the instruments home and build the ideas you already generated. You will have up to a week time to return them. If you return your ideas built, that will be considered as superior effort and you will be given additional extra credit in your design class. This is fully voluntary.

Thank you for your participation and I will make sure that you will receive your extra credit. This concludes your portion of the study. Please remember to not discuss this study with your classmates until after May 1, 2010 since this will bias the data. If you have any questions about this study I can answer them at this time. "

Collect the e-mail id of the participant. At the end scan the drawing sheet and send them.

3. Experimenter Script – Building & Testing Condition
(Some of the instructions are recorded and played from a computer)

Check list:

- Paper to sketch – Taped down to the table
- Computer of the experimenter – Connected to the projector, playlist of instructions and the training loaded
- Speakers
- Projector – with remote control
- Multicolored pens
- Box of prototyping materials
- Participant consent forms
- Print out of the problem description – taped down and covered.
- Survey
- Stop watch
- Numbered address labels
- Press
- Steel wire pieces – 9” long
- Blank sheet for demo
- Time recording sheet
- Print outs of pictures of paperclips
- Box on the table to keep the watches, pens and mobiles
- 10 sheets of blank sheets for testing

16. Consent

On the table:

- Participant consent forms
- BLACK pen
- Taped down paper
- Design problem taped down and covered.
- Projector on

When participants come, show them the work place.

Start stop watch.

“Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. So, please keep your watches and cell phones in your back pack or the box on this table “(Show the box). **“Also please don’t use your pens to sketch.”**

Check to make sure that the participants have no mobiles or watches with them.

“You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

You will be asked to complete a series of tasks. You will be asked to generate ideas for a design problem with a short survey at the end of the experiment. The study will require approximately 3 hours. Please let me know if you have any questions about the experiment.”

Wait until all of the participants have finished reading to proceed with the experiment. Then say**, “If you agree to participate please sign the form and keep the second copy for your records.”**

Wait for participants to sign the consent forms

Collect the consent forms.

“Please put away your copy of the consent forms.”

This experiment has multiple activities and all three hours will be required. Your effort will be compensated with extra credits for your design class. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after May 1, 2010 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

Record the questions and answers in case of any.

Answer the questions if any.

17. Design problem – Building & Testing

Uncover the design problem on the table.

“OK, now we are beginning with the experiment. In this experiment, you are required to build the prototypes of your ideas using steel wire. For helping you in this, we have a recorded training for you. Please look at the projection.”

Play Training.

Play file 1.

“**Are there any questions?”**

Answer if any.

“OK, you may start the idea generation process.”

After 15, 20, 30, 40 …. Min “I will exchange your pens now”…. Exchange with next pen

(Refer color chart for the order of pens)

****** BREAK 1.00 hr ********* “**You will have a 5 min break now. Restrooms are outside and there is a water fountain right across the corner. Please be back on time**”

At 1 hr 35 min “**Please stop the activity**”

18. Follow up Sketching

Play file 2

Are there any questions?

Answer if any.

“OK, you may start the idea generation process.”

****** BREAK 1.55 hrs ********* “**You will have another 5 min break now. Please be back on time**”

After 2 hr 15 min, **“Please stop the activity”**

19. Building additional ideas

Play file 3

Are there any questions?

Answer if any.

“OK, you may start now.”

After 2 hr 25 min, **“Please stop the activity”**

20. *Testing*

Add to the table

- 10 sheets of paper
- BERRY sketch pen
- Address labels

Remove

- The current sketch pen

Play file 3 in the play list.

Answer the questions if any.

"You may begin now"

After 2 hr 30 min… **"Please stop the activity"**

21. *Paper clips seen*

Add to the table

- BROWN sketch pen

Remove

- BERRY sketch pen

Play file 4 in the play list.

"You may begin now."

After 2 hr 35 min **"Please stop the activity"**

Switch off speakers

22. *Sketching vs Building time*

Add to the table

- Pencil
- Printouts of the paperclip pictures

Remove

- BROWN sketch pen

"The purpose of the next activity is to measure your skill in sketching and building. For this purpose, please sketch the wire paper clip shown on the paper in front of you, as quickly and accurately as possible. Please use a fresh box for drawing the clips. The time required will be measured. Please raise your hand when you finish the activity. Are there any questions?"

Answer the questions if any.

"You may begin now. " Start stop watch

When participant raise hand, record the time

"Now we are going to measure your building skill. For that, please make the prototype of the paper clip that you have drawn just now, as quickly and accurately as possible, using the tools and steel wire provided to you. The time required will be measured. Please raise your hand once you are done. Are there any questions?"

Answer the questions if any.

"You may begin now."

When participant raise hand, record the time

"Please sketch the wire paper clip shown on paper in front of you. Remember, we are measuring your sketching skill again, so try to do it as quickly and accurately as possible. Please use a fresh box for drawing the clips. The time required will be measured. Please raise your hand when you finish the activity. You may start now."

When participant raise hand, record the time

"Finally, we are going to measure your building skill again. So please make the prototype of the paper clip you have just drawn, as quickly and accurately as possible, using the tools and steel wire provided to you. The time required will be measured. Please raise your hand once you are done. You may start now."

When participant raise hand, record the time

23. Survey

Add to the table

- Survey
- Pen

Remove

- Pencil

"This is the final part of the experiment. Please fill out the given survey"

Collect the surveys when finished.

24. Disbursement

"You may take the steel wire and the instruments home and build the ideas you already generated. You will have up to a week time to return them. If you return your ideas built, that will be considered as superior effort and you will be given additional extra credit in your design class. This is fully voluntary.

Thank you for your participation and I will make sure that you will receive your extra credit. This concludes your portion of the study. Please remember to not discuss this study with your classmates until after May 1, 2010 since this will bias the data. If you have any questions about this study I can answer them at this time. "

Collect the e-mail id of the participant. At the end scan the drawing sheet and send them.

4. Experimenter Script – Constrained Sketching Condition

(Some of the instructions are recorded and played from a computer)

Check list:

- Paper to sketch – Taped down to the table
- Computer of the experimenter – Connected to the projector, playlist of instructions and the training loaded
- Speakers
- Projector – with remote control
- Multicolored pens
- Box of prototyping materials
- Participant consent forms
- Print out of the problem description – taped down and covered.
- Survey

- Stop watch
- Numbered address labels
- Press
- Steel wire pieces – 9” long
- Blank sheet for demo
- Time recording sheet
- Print outs of pictures of paperclips
- Box on the table to keep the watches, pens and mobiles
- 10 sheets of blank sheets for testing

25. Consent

On the table:

- Participant consent forms
- BLACK pen
- Taped down paper
- Design problem taped down and covered.
- Projector on

When participants come, show them the work place.

Start stop watch.

“Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. So, please keep your watches and cell phones in your back pack or the box on this table “(Show the box). **“Also please don’t use your pens to sketch.”**

Check to make sure that the participants have no mobiles or watches with them.

“You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

You will be asked to complete a series of tasks. You will be asked to generate ideas for a design problem with a short survey at the end of the experiment. The study will require approximately 3 hours. Please let me know if you have any questions about the experiment.”

Wait until all of the participants have finished reading to proceed with the experiment. Then say, **“If you agree to participate please sign the form and keep the second copy for your records.”**

Wait for participants to sign the consent forms

Collect the consent forms.

"Please put away your copy of the consent forms."

This experiment has multiple activities and all three hours will be required. Your effort will be compensated with extra credits for your design class. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after May 1, 2010 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

Record the questions and answers in case of any.

Answer the questions if any.

26. Design problem - Sketching

Uncover the design problem on the table.

"OK, now we are beginning with the experiment. In this experiment, you are required to build the prototypes of your ideas using steel wire. For helping you in this, we have a recorded training for you. Please look at the projection."

Play the training demo.

Turn off the projector.

Play file 1 in the play list.

Answer the questions if any.

"Please raise your hand if you need additional paper or if you have any questions"

"OK, you may start now."

After 15, 20, 30, 40 …. Min "**I will exchange your pens now**"…. Exchange with next pen

****** BREAK 1.00 hr ********* "**You will have a 5 min break now. Restrooms are outside and there is a water fountain right across the corner. Please be back on time**"

After 1 hr 45 min, **"Please stop the activity"**

****** BREAK 1.00 hr 45 min ********* "**You will have another 5 min break now**"

27. Design problem – Building

On the table

- Box of prototyping materials
- PINK sketch pen

Remove

- PURPLE pen

Play file 2 in the play list.

Answer the questions if any.

"Please raise your hand if you need additional paper or if you have any questions"

You may start now.

After 2 hr 10 min "**I will exchange your pens now**"…. Exchange with RED (sketch) pen

After 1 hr 45 min, **"Please stop the activity"**

28. Testing

Add to the table

- 10 sheets of paper
- BERRY sketch pen
- Address labels

Remove

- RED sketch pen

Play file 3 in the play list.

Answer the questions if any. **"You may begin now"**

After 2 hr 30 min… **"Please stop the activity"**

29. Paper clips seen

Add to the table

- BROWN sketch pen

Remove

- BERRY sketch pen

Play file 4 in the play list.

“You may begin now.”

After 2 hr 35 min **“Please stop the activity”**

Switch off speakers

30. Sketching vs Building time

Add to the table

- Pencil
- Printouts of the paperclip pictures

Remove

- BROWN sketch pen

“The purpose of the next activity is to measure your skill in sketching and building. For this purpose, please sketch the wire paper clip shown on the paper in front of you, as quickly and accurately as possible. Please use a fresh box for drawing the clips. The time required will be measured. Please raise your hand when you finish the activity. Are there any questions?”

Answer the questions if any.

“You may begin now. “ Start stop watch

When participant raise hand, record the time

“Now we are going to measure your building skill. For that, please make the prototype of the paper clip that you have drawn just now, as quickly and accurately as possible, using the tools and steel wire provided to you. The time required will be measured. Please raise your hand once you are done. Are there any questions?”

Answer the questions if any.

“You may begin now.”

When participant raise hand, record the time

“Please sketch the wire paper clip shown on paper in front of you. Remember, we are measuring your sketching skill again, so try to do it as quickly and accurately as possible.

Please use a fresh box for drawing the clips. The time required will be measured. Please raise your hand when you finish the activity. You may start now."

When participant raise hand, record the time

"Finally, we are going to measure your building skill again. So please make the prototype of the paper clip you have just drawn, as quickly and accurately as possible, using the tools and steel wire provided to you. The time required will be measured. Please raise your hand once you are done. You may start now."

When participant raise hand, record the time

31. <u>Survey</u>

Add to the table

- Survey
- Pen

Remove

- Pencil

"This is the final part of the experiment. Please fill out the given survey"

Collect the surveys when finished.

32. <u>Disbursement</u>

"You may take the steel wire and the instruments home and build the ideas you already generated. You will have up to a week time to return them. If you return your ideas built, that will be considered as superior effort and you will be given additional extra credit in your design class. This is fully voluntary.

Thank you for your participation and I will make sure that you will receive your extra credit. This concludes your portion of the study. Please remember to not discuss this study with your classmates until after May 1, 2010 since this will bias the data. If you have any questions about this study I can answer them at this time. "

Record the questions and answers in case of any.

Collect the e-mail id of the participant. At the end scan the drawing sheet and send them.

5. Post Experiment Survey – Sketching Only Condition

1) During which part of the study did you generate the **most ideas**? If two are equal, please circle both answers.
    a. I. Sketching only
    b. II. Building prototypes and sketching
    c. III. Testing

2) During which part of the study do you feel like you had the **highest quality ideas**? If two are equal, please circle both answers.
    a. I. Sketching only
    b. II. Building prototypes and sketching
    c. III. Testing

3) Which method do you feel helped you to **generate ideas that functioned the best**? If two are equal, please circle both answers.
    a. I. Sketching only
    b. II. Building prototypes and sketching
    c. III. Testing

4) Had you heard about this experiment or the design problem before coming to the study today? (Your answer does not affect your compensation in any way)
    a. No.
    b. Yes, but I did not know many details.
    c. Yes, and I had thought about potential solutions before coming to this study.

	Strongly Disagree	Disagree	Agree	Strongly Agree
I ran out of **time** before I ran out of ideas.				

Short answer questions.

1) How did being able to sketch affect your ideas?

2) How did being able to build prototypes affect your ideas?

3) How did being able to test your prototypes affect your ideas?

4) Were there any additional materials for building prototypes that would have been useful in the study? If so, what are they?

5) Was the training video for making prototypes useful? How might it be improved?

1) What is your sex?
    a. Female
    b. Male

2) What is your age?______________

3) Overall GPA _______________

4) GPA in Major _______________
5) Year in School
    Undergraduate:
        Freshman
        Sophomore
        Junior
        Senior
    Graduate:
        1st year
        2nd year
        3rd
        4th
        5 or more
6) Country where your undergraduate university is located ____________________

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

Thank you for your time.

6. Post Experiment Survey – Building Condition

1) During which part of the study did you generate the **most ideas**? If two are equal, please circle both answers.
    d. I. Sketching & Building Prototypes
    e. II. Testing

2) During which part of the study do you feel like you had the **highest quality ideas**? If two are equal, please circle both answers.
    f. I. Sketching & Building Prototypes
    g. II. Testing

3) Which method do you feel helped you to **generate ideas that functioned the best**? If two are equal, please circle both answers.
    h. I. Sketching & Building Prototypes
    i. II. Testing

4) Had you heard about this experiment or the design problem before coming to the study today? (Your answer does not affect your compensation in any way)
    j. No.
    k. Yes, but I did not know many details.
    l. Yes, and I had thought about potential solutions before coming to this study.

	Strongly Disagree	Disagree	Agree	Strongly Agree
I ran out of **time** before I ran out of ideas.				

Short answer questions.

6) How did being able to sketch affect your ideas?

7) How did being able to build prototypes affect your ideas?

8) How did being able to test your prototypes affect your ideas?

9) Were there any additional materials for building prototypes that would have been useful in the study? If so, what are they?

10) Was the training video for making prototypes useful? How might it be improved?

1) What is your sex?
   c. Female
   d. Male

2) What is your age?______________

3) Overall GPA _______________

4) GPA in Major _______________
5) Year in School
      Undergraduate:
         Freshman
         Sophomore
         Junior
         Senior
      Graduate:
         1st year
         2nd year
         3rd
         4th
         5 or more
6) Country where your undergraduate university is located ____________________

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

Thank you for your time.

7. Post Experiment Survey – Building & Testing Condition

5) During which part of the study did you generate the **most ideas**? If two are equal, please circle both answers.
   a. I. Building prototypes and testing
   b. II. Sketching only
   c. III. Testing
   d. IV. Continue Generating Ideas, Building& Testing

6) During which part of the study do you feel like you had the **highest quality ideas**? If two are equal, please circle both answers.
   a. I. Building prototypes and testing
   b. II. Sketching only
   c. III. Testing
   d. IV. Continue Generating Ideas, Building& Testing

7) Which method do you feel helped you to **generate ideas that functioned the best**? If two are equal, please circle both answers.
   a. I. Building prototypes and testing
   b. II. Sketching only
   c. III. Testing
   d. IV. Continue Generating Ideas, Building& Testing

8) Had you heard about this experiment or the design problem before coming to the study today? (Your answer does not affect your compensation in any way)
   a. No.
   b. Yes, but I did not know many details.
   c. Yes, and I had thought about potential solutions before coming to this study.

	Strongly Disagree	Disagree	Agree	Strongly Agree
I ran out of **time** before I ran out of ideas.				

Short answer questions.

11) How did being able to build prototypes affect your ideas?

12) How did being able to sketch affect your ideas?

13) How did being able to test your prototypes affect your ideas?

14) Were there any additional materials for building prototypes that would have been useful in the study? If so, what are they?

15) Was the training video for making prototypes useful? How might it be improved?

7) What is your sex?
   e. Female
   f. Male

8) What is your age?_______________

9) Overall GPA ________________

10) GPA in Major ________________
11) Year in School
    - Undergraduate:
        - Freshman
        - Sophomore
        - Junior
        - Senior
    - Graduate:
        - 1st year
        - 2nd year
        - 3rd
        - 4th
        - 5 or more
12) Country where your undergraduate university is located _____________________

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

Thank you for your time.

8. Post Experiment Survey – Constrained Sketching Condition

7) During which part of the study did you generate the **most ideas**? If two are equal, please circle both answers.
   d. I. Sketching only
   e. II. Building prototypes and sketching
   f. III. Testing
   g. IV. Continue Generating Ideas, Building& Testing

8) During which part of the study do you feel like you had the **highest quality ideas**? If two are equal, please circle both answers.
   h. I. Sketching only
   i. II. Building prototypes and sketching
   j. III. Testing
   k. IV. Continue Generating Ideas, Building& Testing

9) Which method do you feel helped you to **generate ideas that functioned the best**? If two are equal, please circle both answers.
   l. I. Sketching only
   m. II. Building prototypes and sketching
   n. III. Testing
   o. IV. Continue Generating Ideas, Building& Testing

10) Had you heard about this experiment or the design problem before coming to the study today? (Your answer does not affect your compensation in any way)
    p. No.
    q. Yes, but I did not know many details.
    r. Yes, and I had thought about potential solutions before coming to this study.

	Strongly Disagree	Disagree	Agree	Strongly Agree
I ran out of **time** before I ran out of ideas.				

Short answer questions.

16) How did being able to sketch affect your ideas?

17) How did being able to build prototypes affect your ideas?

18) How did being able to test your prototypes affect your ideas?

19) Were there any additional materials for building prototypes that would have been useful in the study? If so, what are they?

20) Was the training video for making prototypes useful? How might it be improved?

11) What is your sex?
    g. Female
    h. Male

12) What is your age?______________

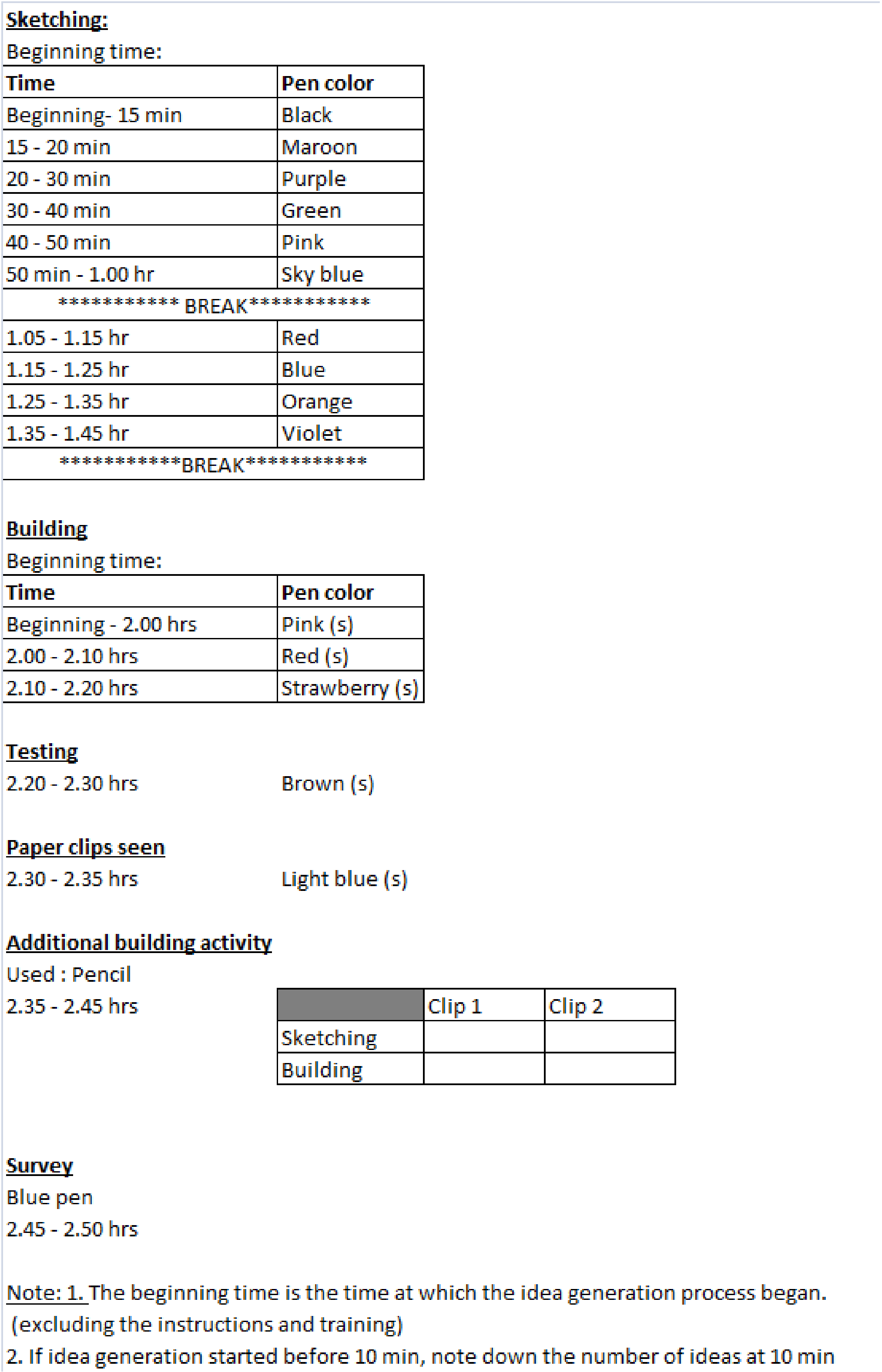
13) Overall GPA _______________

14) GPA in Major _______________
15) Year in School
    - Undergraduate:
        - Freshman
        - Sophomore
        - Junior
        - Senior
    - Graduate:
        - 1st year
        - 2nd year
        - 3rd
        - 4th
        - 5 or more
16) Country where your undergraduate university is located ____________________

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

Thank you for your time.

9. Time Line and Pen Change Log – Sketching Only Condition



Sketching:

Beginning time:

Time	Pen color
Beginning- 15 min	Black
15 - 20 min	Maroon
20 - 30 min	Purple
30 - 40 min	Green
40 - 50 min	Pink
50 min - 1.00 hr	Sky blue
*********** BREAK***********	
1.05 - 1.15 hr	Red
1.15 - 1.25 hr	Blue
1.25 - 1.35 hr	Orange
1.35 - 1.45 hr	Violet
***********BREAK***********	

Building

Beginning time:

Time	Pen color
Beginning - 2.00 hrs	Pink (s)
2.00 - 2.10 hrs	Red (s)
2.10 - 2.20 hrs	Strawberry (s)

Testing

2.20 - 2.30 hrs	Brown (s)

Paper clips seen

2.30 - 2.35 hrs	Light blue (s)

Additional building activity

Used : Pencil

2.35 - 2.45 hrs

	Clip 1	Clip 2
Sketching		
Building		

Survey

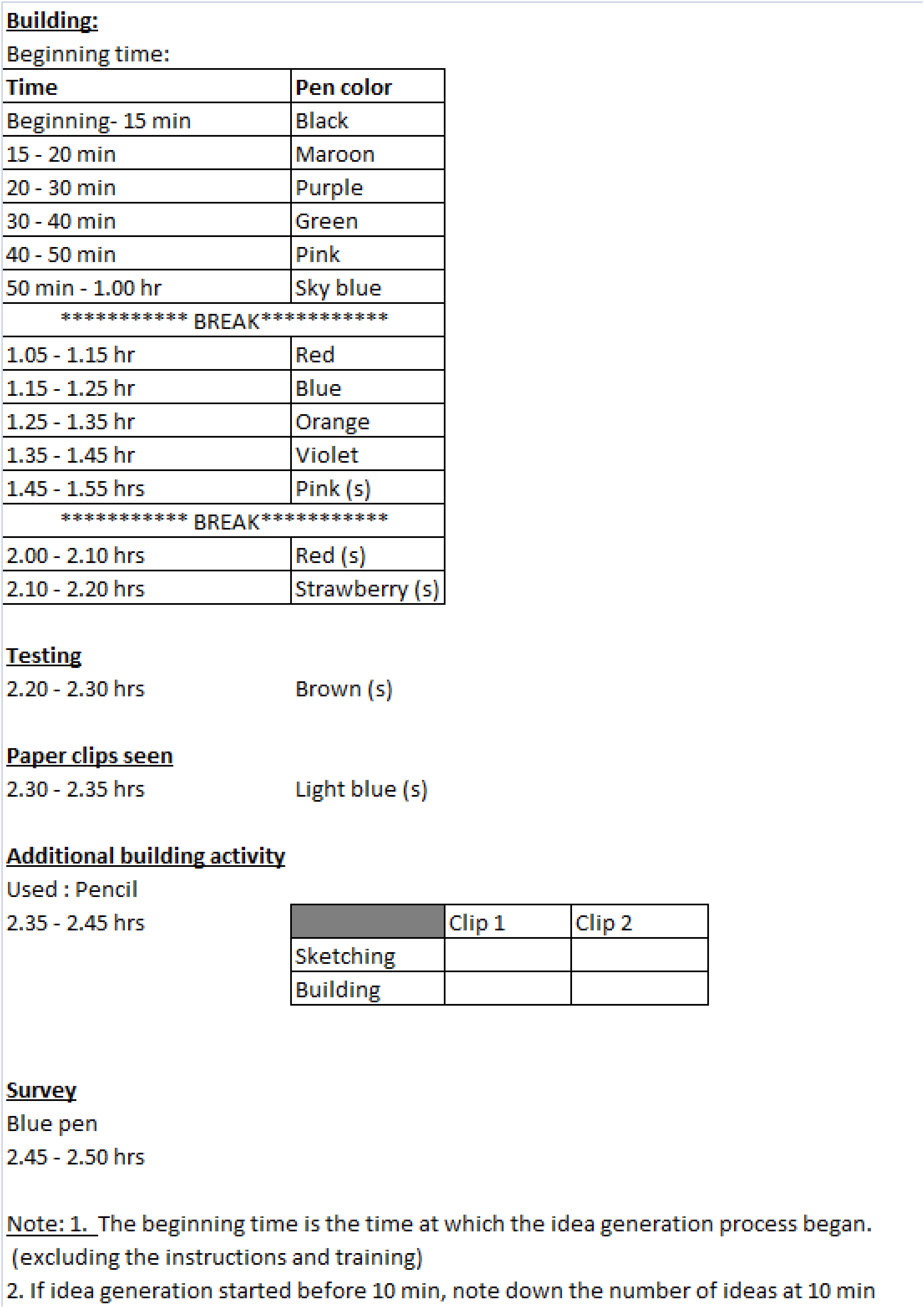
Blue pen

2.45 - 2.50 hrs

Note: 1. The beginning time is the time at which the idea generation process began. (excluding the instructions and training)

2. If idea generation started before 10 min, note down the number of ideas at 10 min

10. Time Line and Pen Change Log – Building Condition



Building:

Beginning time:

Time	**Pen color**
Beginning- 15 min	Black
15 - 20 min	Maroon
20 - 30 min	Purple
30 - 40 min	Green
40 - 50 min	Pink
50 min - 1.00 hr	Sky blue
*********** BREAK***********	
1.05 - 1.15 hr	Red
1.15 - 1.25 hr	Blue
1.25 - 1.35 hr	Orange
1.35 - 1.45 hr	Violet
1.45 - 1.55 hrs	Pink (s)
*********** BREAK***********	
2.00 - 2.10 hrs	Red (s)
2.10 - 2.20 hrs	Strawberry (s)

Testing

2.20 - 2.30 hrs	Brown (s)

Paper clips seen

2.30 - 2.35 hrs	Light blue (s)

Additional building activity

Used : Pencil

2.35 - 2.45 hrs

	Clip 1	Clip 2
Sketching		
Building		

Survey

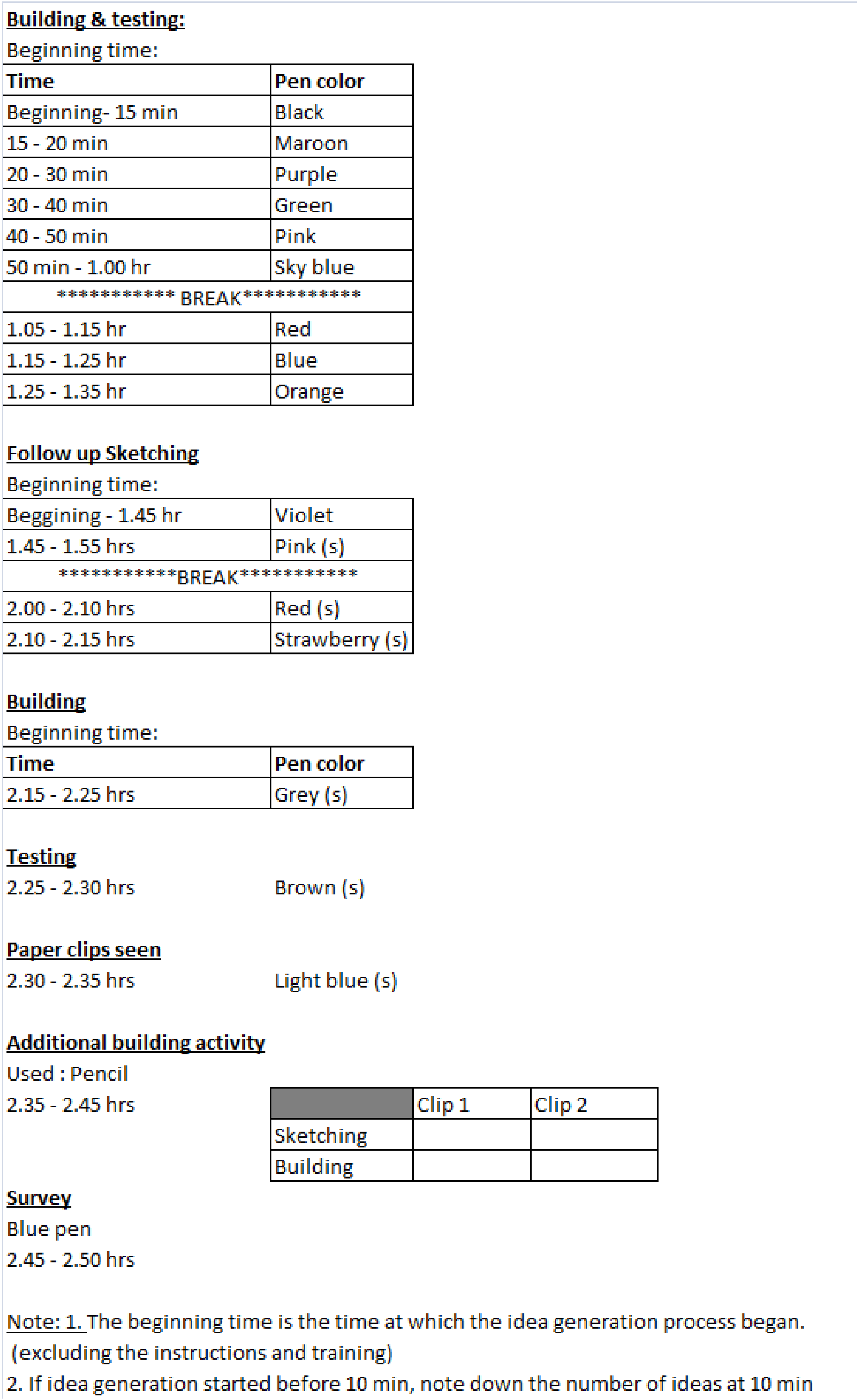
Blue pen

2.45 - 2.50 hrs

Note: 1. The beginning time is the time at which the idea generation process began. (excluding the instructions and training)

2. If idea generation started before 10 min, note down the number of ideas at 10 min

11. Time Line and Pen Change Log – Building & Testing Condition



Building & testing:

Beginning time:

Time	Pen color
Beginning- 15 min	Black
15 - 20 min	Maroon
20 - 30 min	Purple
30 - 40 min	Green
40 - 50 min	Pink
50 min - 1.00 hr	Sky blue
*********** BREAK***********	
1.05 - 1.15 hr	Red
1.15 - 1.25 hr	Blue
1.25 - 1.35 hr	Orange

Follow up Sketching

Beginning time:

Beggining - 1.45 hr	Violet
1.45 - 1.55 hrs	Pink (s)
***********BREAK***********	
2.00 - 2.10 hrs	Red (s)
2.10 - 2.15 hrs	Strawberry (s)

Building

Beginning time:

Time	Pen color
2.15 - 2.25 hrs	Grey (s)

Testing

2.25 - 2.30 hrs	Brown (s)

Paper clips seen

2.30 - 2.35 hrs	Light blue (s)

Additional building activity

Used : Pencil

2.35 - 2.45 hrs

	Clip 1	Clip 2
Sketching		
Building		

Survey

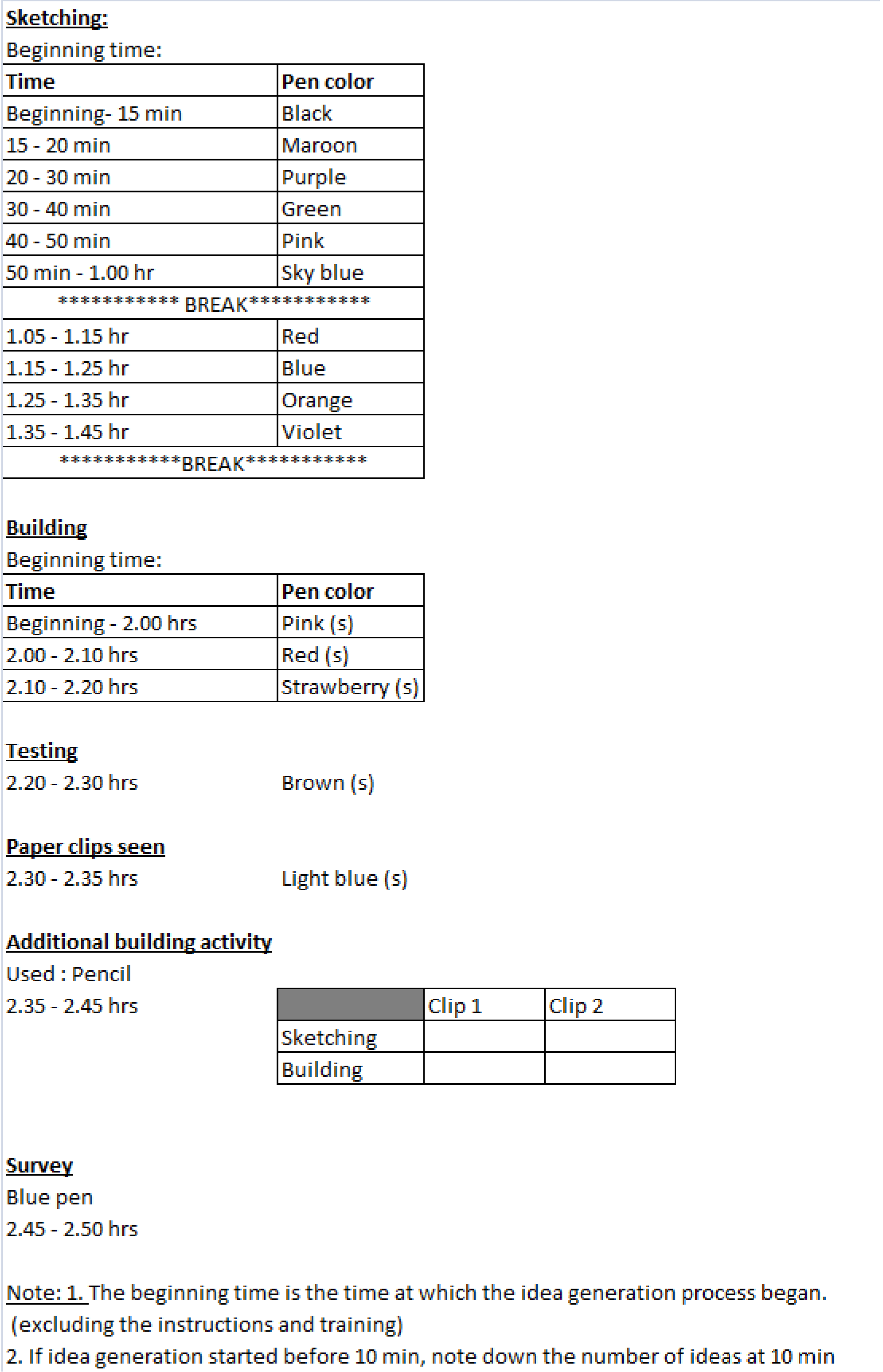
Blue pen

2.45 - 2.50 hrs

Note: 1. The beginning time is the time at which the idea generation process began. (excluding the instructions and training)

2. If idea generation started before 10 min, note down the number of ideas at 10 min

12. Time Line and Pen Change Log – Constrained Sketching Condition



Sketching:

Beginning time:

Time	Pen color
Beginning- 15 min	Black
15 - 20 min	Maroon
20 - 30 min	Purple
30 - 40 min	Green
40 - 50 min	Pink
50 min - 1.00 hr	Sky blue
*********** BREAK***********	
1.05 - 1.15 hr	Red
1.15 - 1.25 hr	Blue
1.25 - 1.35 hr	Orange
1.35 - 1.45 hr	Violet
***********BREAK***********	

Building

Beginning time:

Time	Pen color
Beginning - 2.00 hrs	Pink (s)
2.00 - 2.10 hrs	Red (s)
2.10 - 2.20 hrs	Strawberry (s)

Testing

2.20 - 2.30 hrs	Brown (s)

Paper clips seen

2.30 - 2.35 hrs	Light blue (s)

Additional building activity

Used : Pencil

2.35 - 2.45 hrs

	Clip 1	Clip 2
Sketching		
Building		

Survey

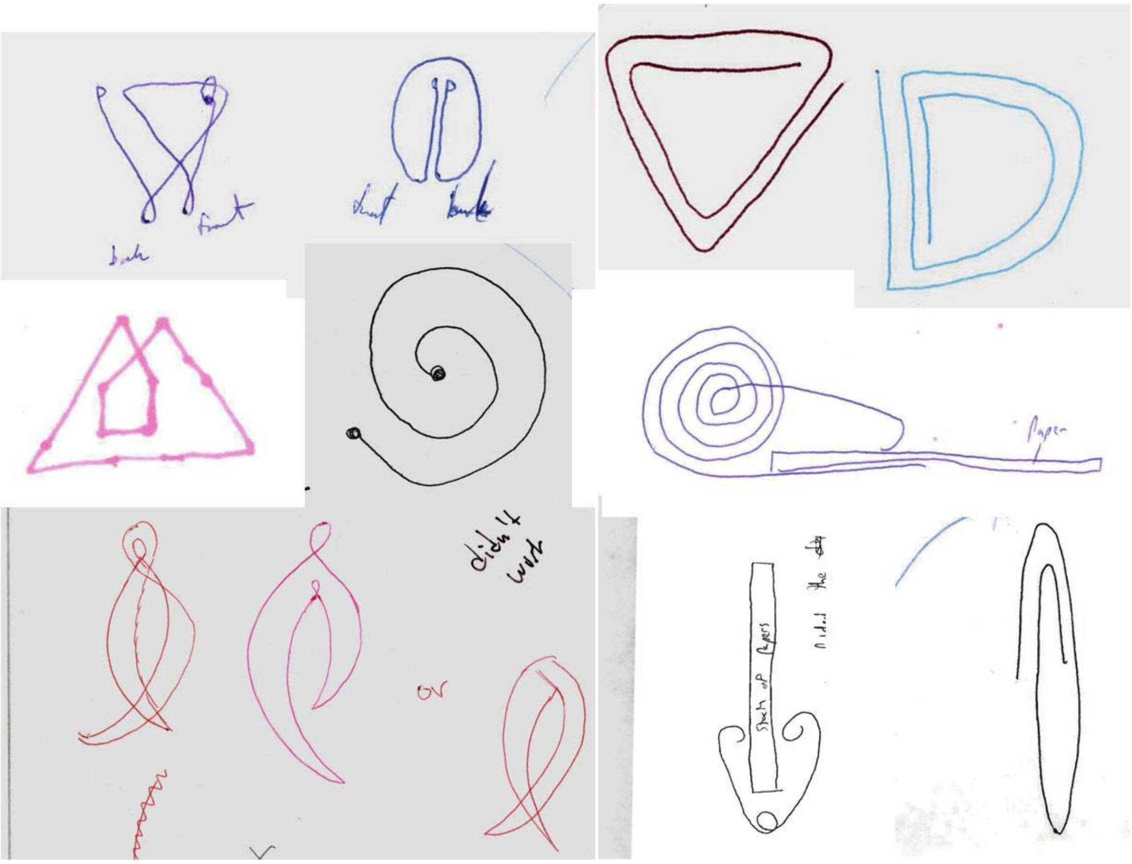
Blue pen

2.45 - 2.50 hrs

Note: 1. The beginning time is the time at which the idea generation process began. (excluding the instructions and training)

2. If idea generation started before 10 min, note down the number of ideas at 10 min

13. <u>Examples of Ideas Generated by Participants</u>



APPENDIX B

EXPERIMENT MATERIALS AND DATA FROM THE SUNK COST EXPERIMENT

1. Experimenter Script – Sketching Only Condition
(Some of the instructions are recorded and played from a computer)

Check list:

- o Paper to sketch – Taped down to the table
- o Computer of the experimenter – Connected to the projector, playlist of instructions and the training loaded
- o Speakers
- o Projector – with remote control
- o Multicolored pens
- o Box of prototyping materials
- o Participant consent forms
- o Print out of the problem description – taped down and covered.
- o Survey
- o Stop watch
- o Numbered address labels
- o Press
- o Steel wire pieces – 9” long
- o Blank sheet for demo
- o Time recording sheet
- o Box on the table to keep the watches, pens and mobiles
- o 10 sheets of blank sheets for testing

1. Consent

On the table:

- Participant consent forms
- BLACK pen
- Taped down paper
- Design problem taped down and covered.
- Projector on

When participants come, show them the work place.

Start stop watch.

“Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. So, please keep your watches and cell phones in your back pack or the box on this table “(Show the box). **“Also please don’t use your pens to sketch.”**

Check to make sure that the participants have no mobiles or watches with them.

“You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

You will be asked to complete a series of tasks. You will be asked to generate ideas for a design problem with a short survey at the end of the experiment. The study will require approximately 3 hours. Please let me know if you have any questions about the experiment.”

Wait until all of the participants have finished reading to proceed with the experiment. Then say**,** **“If you agree to participate please sign the form and keep the second copy for your records.”**

Wait for participants to sign the consent forms

Collect the consent forms.

“Please put away your copy of the consent forms.”

This experiment has multiple activities and all three hours will be required. Your effort will be compensated with extra credits for your design class. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after September 1, 2011 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

Record the questions and answers in case of any.

Answer the questions if any.

2. *Design problem - Sketching*

Uncover the design problem on the table.

“OK, now we are beginning with the experiment. As I already mentioned to you this is based on engineering idea generation process. You are going to create solutions for a real life problem. Please listen to the recorded instructions now.”

Play file 1.

At the end of playback “**Are there any questions?”**

Answer if any.

“OK, you may start the idea generation process.”

After 15, 20, 30, 40 …. Min “I will exchange your pens now”…. Exchange with next pen

****** BREAK 1.00 hr ********* “**You will have a 5 min break now. Restrooms are outside and there is a water fountain right across the corner. Please be back on time**”

After 1 hr 45 min, **“Please stop the activity”**

****** BREAK 1.00 hr 45 min ********* “**You will have another 5 min break now**”

3. *Design problem – Building*

On the table

- Box of prototyping materials
- PINK sketch pen

Remove

- PURPLE pen

“Welcome back. As a part of the experiment, now you are going to build physical prototypes of your ideas. For helping you in this we have a recorded training for you. I will start the training now.”

Play training demo.

Play file 2.

“Are there any questions?”

Answer the questions if any.

You may start now.

After 2 hr 10 min “I will exchange your pens now”…. Exchange with next pen

After 2 hr 20 min "I will exchange your pens now"…. Exchange with next pen

After, 2 hr 30 min, **"Please stop the activity"**

4. *Testing*

Add to the table

- 10 sheets of paper
- BROWN sketch pen
- Address labels

Remove

- The current sketch pen

Play file 3 in the play list.

Answer the questions if any.

"You may begin now"

After 2 hr 30 min… **"Please stop the activity"**

5. *Paper clips seen*

Add to the table

- Pencil

Remove

- BROWN sketch pen

Play file 4 in the play list.

"You may begin now."

After 2 hr 45 min **"Please stop the activity"**

Switch off speakers

6. *Survey*

Add to the table

- Survey
- Pen

Remove

- Pencil

"This is the final part of the experiment. Please fill out the given survey"

Collect the surveys when finished.

7. *Disbursement*

"You may take the steel wire and the instruments home and build the ideas you already generated. You will have up to a week time to return them. If you return your ideas built, that will be considered as superior effort and you will be given additional extra credit in your design class. This is fully voluntary.

Before you leave, I want one more piece of information from you. What is your major?

Thank you for your participation and I will make sure that you will receive your extra credit. This concludes your portion of the study. Please remember to not discuss this study with your classmates until after September 1, 2011 since this will bias the data. If you have any questions about this study I can answer them at this time. "

Collect the e-mail id of the participant. At the end scan the drawing sheet and send them.

2. Experimenter Script – Metal Building Condition

(Some of the instructions are recorded and played from a computer)

Check list:

- o Paper to sketch – Taped down to the table
- o Computer of the experimenter – Connected to the projector, playlist of instructions and the training loaded
- o Speakers
- o Projector – with remote control
- o Multicolored pens
- o Box of prototyping materials
- o Participant consent forms
- o Print out of the problem description – taped down and covered.
- o Survey
- o Stop watch
- o Numbered address labels
- o Press
- o Steel wire pieces – 9" long
- o Blank sheet for demo
- o Time recording sheet
- o Box on the table to keep the watches, pens and mobiles
- o 10 sheets of blank sheets for testing

8. Consent

On the table:

- Participant consent forms
- BLACK pen
- Taped down paper
- Design problem taped down and covered.
- Projector on

When participants come, show them the work place.

Start stop watch.

"Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. So, please keep your watches and cell phones in your back pack or the box on this table "(Show the box). **"Also please don't use your pens to sketch."**

Check to make sure that the participants have no mobiles or watches with them.

“You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

You will be asked to complete a series of tasks. You will be asked to generate ideas for a design problem with a short survey at the end of the experiment. The study will require approximately 3 hours. Please let me know if you have any questions about the experiment.”

Wait until all of the participants have finished reading to proceed with the experiment. Then say**, “If you agree to participate please sign the form and keep the second copy for your records.”**

Wait for participants to sign the consent forms

Collect the consent forms.

“Please put away your copy of the consent forms.”

This experiment has multiple activities and all three hours will be required. Your effort will be compensated with extra credits for your design class. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after September 1, 2011 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

Record the questions and answers in case of any.

Answer the questions if any.

9. Design problem - Building

Uncover the design problem on the table.

“OK, now we are beginning with the experiment. In this experiment, you are required to build the prototypes of your ideas using steel wire. For helping you in this, we have a recorded training for you. Please look at the projection.”

Play Training.

Play file 1.

“**Are there any questions?”**

Answer if any.

“OK, you may start the idea generation process.”

After 15, 20, 30, 40 …. Min "I will exchange your pens now"…. Exchange with next pen

(Refer color chart for the order of pens)

****** BREAK 1.00 hr ********* "**You will have a 5 min break now. Restrooms are outside and there is a water fountain right across the corner. Please be back on time**"

****** BREAK 2.00 hrs ********* "**You will have another 5 min break now. Please be back on time**"

After 2 hr 30 min, **"Please stop the activity"**

10. Testing

Add to the table

- 10 sheets of paper
- BROWN sketch pen
- Address labels

Remove

- The current sketch pen

Play file 3 in the play list.

Answer the questions if any.

"You may begin now"

After 2 hr 40 min… **"Please stop the activity"**

11. Paper clips seen

Add to the table

- Pencil

Remove

- current pen

Play file 4 in the play list.

“You may begin now.”

After 2 hr 35 min **“Please stop the activity”**

Switch off speakers

12. *Survey*

Add to the table

- Survey
- Pen

Remove

- Pencil

“This is the final part of the experiment. Please fill out the given survey”

Collect the surveys when finished.

13. *Disbursement*

“You may take the steel wire and the instruments home and build the ideas you already generated. You will have up to a week time to return them. If you return your ideas built, that will be considered as superior effort and you will be given additional extra credit in your design class. This is fully voluntary.

Before you leave, I want one more piece of information from you. What is your major?

Thank you for your participation and I will make sure that you will receive your extra credit. This concludes your portion of the study. Please remember to not discuss this study

with your classmates until after September 1, 2011 since this will bias the data. If you have any questions about this study I can answer them at this time. "

Collect the e-mail id of the participant. At the end scan the drawing sheet and send them.

3. Experimenter Script – Plastic Building Condition
(Some of the instructions are recorded and played from a computer)

Check list:

- o Paper to sketch – Taped down to the table
- o Multicolored pens
- o Participant consent forms
- o Print out of the problem description – taped down and covered.
- o Survey
- o Stop watch
- o Numbered address labels
- o Time recording sheet
- o Box on the table to keep the watches, pens and mobiles
- o Mold Putty
- o Plastic pellets
- o Hot plate – Switch on and keep on "warm" 10 min before the start
- o Non-stick pan
- o Tongs
- o Armature wire
- o Carving tools
- o Card Board pieces for testing
- o 10 sheets of paper

14. Consent

On the table:

- Participant consent forms
- BLACK pen
- Taped down paper
- Design problem taped down and covered.
- Prototyping materials

When participants come, show them the work place.

Start stop watch.

“Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. So, please keep your watches and cell phones in your back pack or the box on this table “(Show the box). **“Also please don’t use your pens to sketch.”**

Check to make sure that the participants have no mobiles or watches with them.

“You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

You will be asked to complete a series of tasks. You will be asked to generate ideas for a design problem with a short survey at the end of the experiment. The study will require approximately *3 hours*. Please let me know if you have any questions about the experiment.”

Wait until all of the participants have finished reading to proceed with the experiment. Then say**,** **“If you agree to participate please sign the form and keep the second copy for your records.”**

Wait for participants to sign the consent forms

Collect the consent forms.

“Please put away your copy of the consent forms.”

This experiment has multiple activities and all *3 hours* will be required. Your effort will be compensated with $20 paid immediately at the end of the experiment or extra credits for your design class. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after September 1, 2011 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

Record the questions and answers in case of any.

Answer the questions if any.

15. <u>Design problem - Building</u>

“OK, now we are beginning with the experiment. In this experiment, you are required to build the prototypes of your ideas using plastic. For helping you in this, we have a recorded training for you. Please turn your chair so that you can see the projection. Try to follow along as various activities are shown on the screen. This will help you to get some practice”

Play training video

Are there any questions?

Answer if any

Play file 1

Are there any questions?

Answer if any.

“OK, you may start the idea generation process.”

After 5, 10, 15, 20, 30, 40 …. Min “I will exchange your pens now”…. Exchange with next pen

(Refer color chart for the order of pens)

Check whether the participant has sketched all the ideas they build. If not ask them to sketch. Also, check whether they have built all the ideas they have sketched. If not ask them to build it or put an “X” if they cannot build them.

****** BREAK 1.00 hr ********* “**You will have a 5 min break now. Restrooms are outside and there is a water fountain right across the corner. Please be back on time**”

****** BREAK 2.00 hrs *********

After 2 hrs 30 min, **“Please stop the activity”**

16. *Testing*

Add to the table

- Card Board sheets & 10 sheets of paper
- Pen
- Address labels

Remove

- Current pen

Play file 2

Are there any questions?

Answer the questions if any.

“You may begin now”

After 2 hrs 40 min **“Please stop the activity”**

17. Paper clips seen

Add to the table

- Pencil

Remove

- Current pen

Play file 3

Are there any questions?

Answer if any.

“You may begin now.”

After 2 hrs 45 min **“Please stop the activity”**

18. Survey

Add to the table

- Survey
- Pen

“This is the final part of the experiment. Please fill out the given survey”

Collect the surveys when finished.

19. Disbursement

Thank you for your participation.

Before you leave, I want one more piece of information from you. What is your major?

Thank you for your participation and here is your payment voucher/I will make sure that you will receive your extra credit. This concludes your portion of the study. Please remember to not discuss this study with your classmates until after September 1, 2011 since this will bias the data. If you have any questions about this study I can answer them at this time. "

4. Experimenter Script – Metal Constrained Sketching Condition
   (Some of the instructions are recorded and played from a computer)

Check list:

- o Paper to sketch – Taped down to the table
- o Computer of the experimenter – Connected to the projector, playlist of instructions and the training loaded
- o Speakers
- o Projector – with remote control
- o Multicolored pens
- o Box of prototyping materials
- o Participant consent forms
- o Print out of the problem description – taped down and covered.
- o Survey
- o Stop watch
- o Numbered address labels
- o Press
- o Steel wire pieces – 9" long
- o Blank sheet for demo
- o Time recording sheet
- o Box on the table to keep the watches, pens and mobiles
- o 10 sheets of blank sheets for testing

20. Consent

    On the table:
    - Participant consent forms
    - BLACK pen
    - Taped down paper
    - Design problem taped down and covered.
    - Projector on

When participants come, show them the work place.

Start stop watch.

"Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. So, please keep your watches and cell phones in your back pack or the box on this table "(Show the box). **"Also please don't use your pens to sketch."**

Check to make sure that the participants have no mobiles or watches with them.

"You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

You will be asked to complete a series of tasks. You will be asked to generate ideas for a design problem with a short survey at the end of the experiment. The study will require approximately 3 hours. Please let me know if you have any questions about the experiment."

Wait until all of the participants have finished reading to proceed with the experiment. Then say**, "If you agree to participate please sign the form and keep the second copy for your records."**

Wait for participants to sign the consent forms

Collect the consent forms.

"Please put away your copy of the consent forms."

This experiment has multiple activities and all three hours will be required. Your effort will be compensated with extra credits for your design class. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after September 1, 2011 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

Record the questions and answers in case of any.

Answer the questions if any.

21. <u>Design problem - Sketching</u>

Uncover the design problem on the table.

"OK, now we are beginning with the experiment. In this experiment, you are required to build the prototypes of your ideas using steel wire. For helping you in this, we have a recorded training for you. Please look at the projection."

Play the training demo.

Turn off the projector.

Play file 1 in the play list.

Answer the questions if any.

"Please raise your hand if you need additional paper or if you have any questions"

"OK, you may start now."

After 15, 20, 30, 40 …. Min "**I will exchange your pens now**"…. Exchange with next pen

****** BREAK 1.00 hr ********* "**You will have a 5 min break now. Restrooms are outside and there is a water fountain right across the corner. Please be back on time**"

After 1 hr 45 min, **"Please stop the activity"**

****** BREAK 1.00 hr 45 min ********* "**You will have another 5 min break now**"

22. <u>Design problem – Building</u>

On the table

- Box of prototyping materials
- PINK sketch pen

Remove

- PURPLE pen

Play file 2 in the play list.

Answer the questions if any.

"Please raise your hand if you need additional paper or if you have any questions"

You may start now.

After 2 hr 10 min "**I will exchange your pens now**"…. Exchange with RED (sketch) pen

After 1 hr 45 min, **"Please stop the activity"**

23. Testing

Add to the table

- 10 sheets of paper
- BROWN sketch pen
- Address labels

Remove

- Current sketch pen

Play file 3 in the play list.

Answer the questions if any. **“You may begin now”**

After 2 hr 30 min… **“Please stop the activity”**

24. Paper clips seen

Add to the table

- Pencil

Remove

- Current sketch pen

Play file 4 in the play list.

“You may begin now.”

After 2 hr 35 min **“Please stop the activity”**

Switch off speakers

25. Survey

Add to the table

- Survey
- Pen

Remove

- Pencil

"This is the final part of the experiment. Please fill out the given survey"

Collect the surveys when finished.

26. Disbursement

"You may take the steel wire and the instruments home and build the ideas you already generated. You will have up to a week time to return them. If you return your ideas built, that will be considered as superior effort and you will be given additional extra credit in your design class. This is fully voluntary.

Before you leave, I want one more piece of information from you. What is your major?

Thank you for your participation and I will make sure that you will receive your extra credit. This concludes your portion of the study. Please remember to not discuss this study with your classmates until after September 1, 2011 since this will bias the data. If you have any questions about this study I can answer them at this time. "

Record the questions and answers in case of any.

Collect the e-mail id of the participant. At the end scan the drawing sheet and send them.

5. Experimenter Script – Metal Constrained Sketching Condition
(Some of the instructions are recorded and played from a computer)

Check list:

- o Paper to sketch – Taped down to the table
- o Multicolored pens
- o Participant consent forms
- o Print out of the problem description – taped down and covered.
- o Survey
- o Stop watch
- o Numbered address labels
- o Time recording sheet
- o Box on the table to keep the watches, pens and mobiles

- Mold Putty
- Plastic pellets
- Hot plate – Switch on and keep on “warm” 10 min before the start
- Non-stick pan
- Tongs
- Armature wire
- Carving tools
- Card Board pieces for testing
- 10 sheets of paper

27. *Consent*

On the table:

- Participant consent forms
- BLACK pen
- Taped down paper
- Design problem taped down and covered.

When participants come, show them the work place.

Start stop watch.

“Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. So, please keep your watches and cell phones in your back pack or the box on this table “(Show the box). **“Also please don’t use your pens to sketch.”**

Check to make sure that the participants have no mobiles or watches with them.

“You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

You will be asked to complete a series of tasks. You will be asked to generate ideas for a design problem with a short survey at the end of the experiment. The study will require approximately 3 *hours*. Please let me know if you have any questions about the experiment.”

Wait until all of the participants have finished reading to proceed with the experiment. Then say**, “If you agree to participate please sign the form and keep the second copy for your records.”**

Wait for participants to sign the consent forms

Collect the consent forms.

"Please put away your copy of the consent forms."

This experiment has multiple activities and all *3 hours* will be required. Your effort will be compensated with extra credits for your design class. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after September 1, 2011 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

Record the questions and answers in case of any.

Answer the questions if any.

28. *Design problem - Sketching*

Uncover the design problem on the table.

"OK, now we are beginning with the experiment. As I already mentioned to you this is based on engineering idea generation process. You are going to create solutions for a real life problem. You are also required to build the prototypes of your ideas using plastic. For helping you in this, we have a recorded training for you. Please turn your chair so that you can see the projection. Try to follow along as various activities are shown on the screen. This will help you to get some practice"

Play training video

Are there any questions?

Answer if any

Play file 1

Are there any questions?

Answer if any.

"OK, you may start the idea generation process."

After 5, 10, 15, 20, 30, 40 …. Min "I will exchange your pens now"…. Exchange with next pen

(Refer color chart for the order of pens)

Record Time(Use the time recording sheet)

****** BREAK 1.00 hr ********* “**You will have a 5 min break now. Restrooms are outside and there is a water fountain right across the corner. Please be back on time**”

After 2 hrs, **“Please stop the activity”**

****** BREAK *********

29. <u>Building prototypes</u>

Add

- Prototyping materials
- Pen

Remove

- Current pen

Welcome back.

Play file 2

At 2 hr 30 min **“Please stop the activity”**

30. <u>Testing prototypes</u>

Add to the table

- Card Board sheets & 10 sheets of paper
- Pen
- Address labels

Remove

- Current pen

Play file 3

Are there any questions?

Answer the questions if any.

“You may begin now”

After 2 hr 40 min **“Please stop the activity”**

31. *Paper clips seen*

Add to the table

- Pencil

Remove

- Current pen

Play file 4

Are there any questions?

Answer if any.

“You may begin now.”

After 2 hrs 45 min **“Please stop the activity”**

32. *Survey*

Add to the table

- Survey
- Pen

“This is the final part of the experiment. Please fill out the given survey”

Collect the surveys when finished.

33. *Disbursement*

Thank you for your participation.

Before you leave, I want one more piece of information from you. What is your major?

Thank you for your participation and here is your payment voucher/I will make sure that you will receive your extra credit. This concludes your portion of the study. Please

remember to not discuss this study with your classmates until after September 1, 2011 since this will bias the data. If you have any questions about this study I can answer them at this time. "

6. Post-experiment Survey – Sketching Only Condition

1) During which part of the study did you generate the **most ideas**? If two are equal, please circle both answers.
    a. I. Sketching only
    b. II. Building prototypes and sketching
    c. III. Testing

2) During which part of the study do you feel like you had the **highest quality ideas**? If two are equal, please circle both answers.
    a. I. Sketching only
    b. II. Building prototypes and sketching
    c. III. Testing

3) Which method do you feel helped you to **generate ideas that functioned the best**? If two are equal, please circle both answers.
    a. I. Sketching only
    b. II. Building prototypes and sketching
    c. III. Testing

4) Had you heard about this experiment or the design problem before coming to the study today? (Your answer does not affect your compensation in any way)
    a. No.
    b. Yes, but I did not know many details.
    c. Yes, and I had thought about potential solutions before coming to this study.

	Strongly Disagree	Disagree	Agree	Strongly Agree
I ran out of **time** before I ran out of ideas.				

Short answer questions.

1) How did being able to sketch affect your ideas?

2) How did being able to build prototypes affect your ideas?

3) How did being able to test your prototypes affect your ideas?

4) Were there any additional materials for building prototypes that would have been useful in the study? If so, what are they?

5) Was the training video for making prototypes useful? How might it be improved?

1) What is your sex?
    a. Female
    b. Male

2) What is your age?_______________

3) Overall GPA ________________

4) GPA in Major ________________
5) Year in School
    Undergraduate:
        Freshman
        Sophomore
        Junior
        Senior
    Graduate:
        1st year
        2nd year
        3rd
        4th
        5 or more
6) Country where your undergraduate university is located _____________________

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

Thank you for your time.

7. Post-experiment Survey – Metal Building Condition

1) During which part of the study did you generate the **most ideas**? If two are equal, please circle both answers.
   a. I. Sketching & Building Prototypes
   b. II. Testing

2) During which part of the study do you feel like you had the **highest quality ideas**? If two are equal, please circle both answers.
   a. I. Sketching & Building Prototypes
   b. II. Testing

3) Which method do you feel helped you to **generate ideas that functioned the best**? If two are equal, please circle both answers.
   a. I. Sketching & Building Prototypes
   b. II. Testing

4) Had you heard about this experiment or the design problem before coming to the study today? (Your answer does not affect your compensation in any way)
   a. No.
   b. Yes, but I did not know many details.
   c. Yes, and I had thought about potential solutions before coming to this study.

	Strongly Disagree	Disagree	Agree	Strongly Agree
I ran out of **time** before I ran out of ideas.				

Short answer questions.

1) How did being able to sketch affect your ideas?

2) How did being able to build prototypes affect your ideas?

3) How did being able to test your prototypes affect your ideas?

4) Were there any additional materials for building prototypes that would have been useful in the study? If so, what are they?

5) Was the training video for making prototypes useful? How might it be improved?

1) What is your sex?
    c. Female
    d. Male

2) What is your age?_______________

3) Overall GPA ________________

4) GPA in Major ________________
5) Year in School
    Undergraduate:
        Freshman
        Sophomore
        Junior
        Senior
    Graduate:
        1st year
        2nd year
        3rd
        4th
        5 or more
6) Country where your undergraduate university is located ______________________

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

Thank you for your time.

8. Post-experiment Survey – Plastic Building Condition

1) During which part of the study did you generate the **most ideas**? If two are equal, please circle both answers.
   a. I. Sketching & Building Prototypes
   b. II. Testing

2) During which part of the study do you feel like you had the **highest quality ideas**? If two are equal, please circle both answers.
   a. I. Sketching & Building Prototypes
   b. II. Testing

3) Which method do you feel helped you to **generate ideas that functioned the best**? If two are equal, please circle both answers.
   a. I. Sketching & Building Prototypes
   b. II. Testing

4) Had you heard about this experiment or the design problem before coming to the study today? (Your answer does not affect your compensation in any way)
   a. No.
   b. Yes, but I did not know many details.
   c. Yes, and I had thought about potential solutions before coming to this study.

	Strongly Disagree	Disagree	Agree	Strongly Agree
I ran out of **time** before I ran out of ideas.				

Short answer questions.

1) How did being able to sketch affect your ideas?

2) How did being able to build prototypes affect your ideas?

3) How did being able to test your prototypes affect your ideas?

4) Were there any additional materials for building prototypes that would have been useful in the study? If so, what are they?

1) Was the training video for making prototypes useful? How might it be improved?

1) What is your sex?
    e. Female
    f. Male

2) What is your age?______________

3) Overall GPA _______________

4) GPA in Major _______________
5) Year in School
    Undergraduate:
        Freshman
        Sophomore
        Junior
        Senior
    Graduate:
        1st year
        2nd year
        3rd
        4th
        5 or more
6) Country where your undergraduate university is located ____________________

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

Thank you for your time.

9. Post-experiment Survey – Metal Constrained Sketching Condition

1) During which part of the study did you generate the **most ideas**? If two are equal, please circle both answers.
   a. I. Sketching only
   b. II. Building prototypes and sketching
   c. III. Testing
   d. IV. Continue Generating Ideas, Building& Testing

2) During which part of the study do you feel like you had the **highest quality ideas**? If two are equal, please circle both answers.
   a. I. Sketching only
   b. II. Building prototypes and sketching
   c. III. Testing
   d. IV. Continue Generating Ideas, Building& Testing

3) Which method do you feel helped you to **generate ideas that functioned the best**? If two are equal, please circle both answers.
   a. I. Sketching only
   b. II. Building prototypes and sketching
   c. III. Testing
   d. IV. Continue Generating Ideas, Building& Testing

4) Had you heard about this experiment or the design problem before coming to the study today? (Your answer does not affect your compensation in any way)
   a. No.
   b. Yes, but I did not know many details.
   c. Yes, and I had thought about potential solutions before coming to this study.

	Strongly Disagree	Disagree	Agree	Strongly Agree
I ran out of **time** before I ran out of ideas.				

Short answer questions.

1) How did being able to sketch affect your ideas?

2) How did being able to build prototypes affect your ideas?

3) How did being able to test your prototypes affect your ideas?

4) Were there any additional materials for building prototypes that would have been useful in the study? If so, what are they?

5) Was the training video for making prototypes useful? How might it be improved?

1) What is your sex?
    g. Female
    h. Male

2) What is your age?_______________

3) Overall GPA ________________

4) GPA in Major ________________
5) Year in School
    Undergraduate:
        Freshman
        Sophomore
        Junior
        Senior
    Graduate:
        1st year
        2nd year
        3rd
        4th
        5 or more
6) Country where your undergraduate university is located _____________________

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

Thank you for your time.

10. Post-experiment Survey – Plastic Constrained Sketching Condition

1) During which part of the study did you generate the **most ideas**? If two are equal, please circle both answers.
   a. I. Sketching only
   b. II. Building prototypes and sketching
   c. III. Testing

2) During which part of the study do you feel like you had the **highest quality ideas**? If two are equal, please circle both answers.
   a. I. Sketching only
   b. II. Building prototypes and sketching
   c. III. Testing

3) Which method do you feel helped you to **generate ideas that functioned the best**? If two are equal, please circle both answers.
   a. I. Sketching only
   b. II. Building prototypes and sketching
   c. III. Testing

4) Had you heard about this experiment or the design problem before coming to the study today? (Your answer does not affect your compensation in any way)
   a. No.
   b. Yes, but I did not know many details.
   c. Yes, and I had thought about potential solutions before coming to this study.

	Strongly Disagree	Disagree	Agree	Strongly Agree
I ran out of **time** before I ran out of ideas.				

Short answer questions.

1) How did being able to sketch affect your ideas?

2) How did being able to build prototypes affect your ideas?

3) How did being able to test your prototypes affect your ideas?

4) Were there any additional materials for building prototypes that would have been useful in the study? If so, what are they?

5) Was the training video for making prototypes useful? How might it be improved?

1) What is your sex?
    i. Female
    j. Male

2) What is your age?_______________

3) Overall GPA ________________

4) GPA in Major ________________
5) Year in School
    Undergraduate:
        Freshman
        Sophomore
        Junior
        Senior
    Graduate:
        1st year
        2nd year
        3rd
        4th
        5 or more
6) Country where your undergraduate university is located _____________________

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

Thank you for your time.

11. Timeline and Pen Change Log – Sketching Only Condition

Sketching:

Beginning time:

Time	**Pen color**
Beginning- 15 min	Black
15 - 20 min	Maroon
20 - 30 min	Purple
30 - 40 min	Green
40 - 50 min	Pink
50 min - 1.00 hr	Sky blue
*********** BREAK***********	
1.05 - 1.15 hr	Red
1.15 - 1.25 hr	Blue
1.25 - 1.35 hr	Orange
1.35 - 1.45 hr	Violet
***********BREAK***********	

Building

Beginning time:

Time	**Pen color**
Beginning - 2.00 hrs	Pink (s)
2.00 - 2.10 hrs	Red (s)
2.10 - 2.20 hrs	Strawberry (s)
2.20 - 2.30 hrs	Light blue (s)

Testing

2.30 - 2.40 hrs Brown (s)

Paper clips seen

2.40 - 2.45 hrs Pencil

Survey

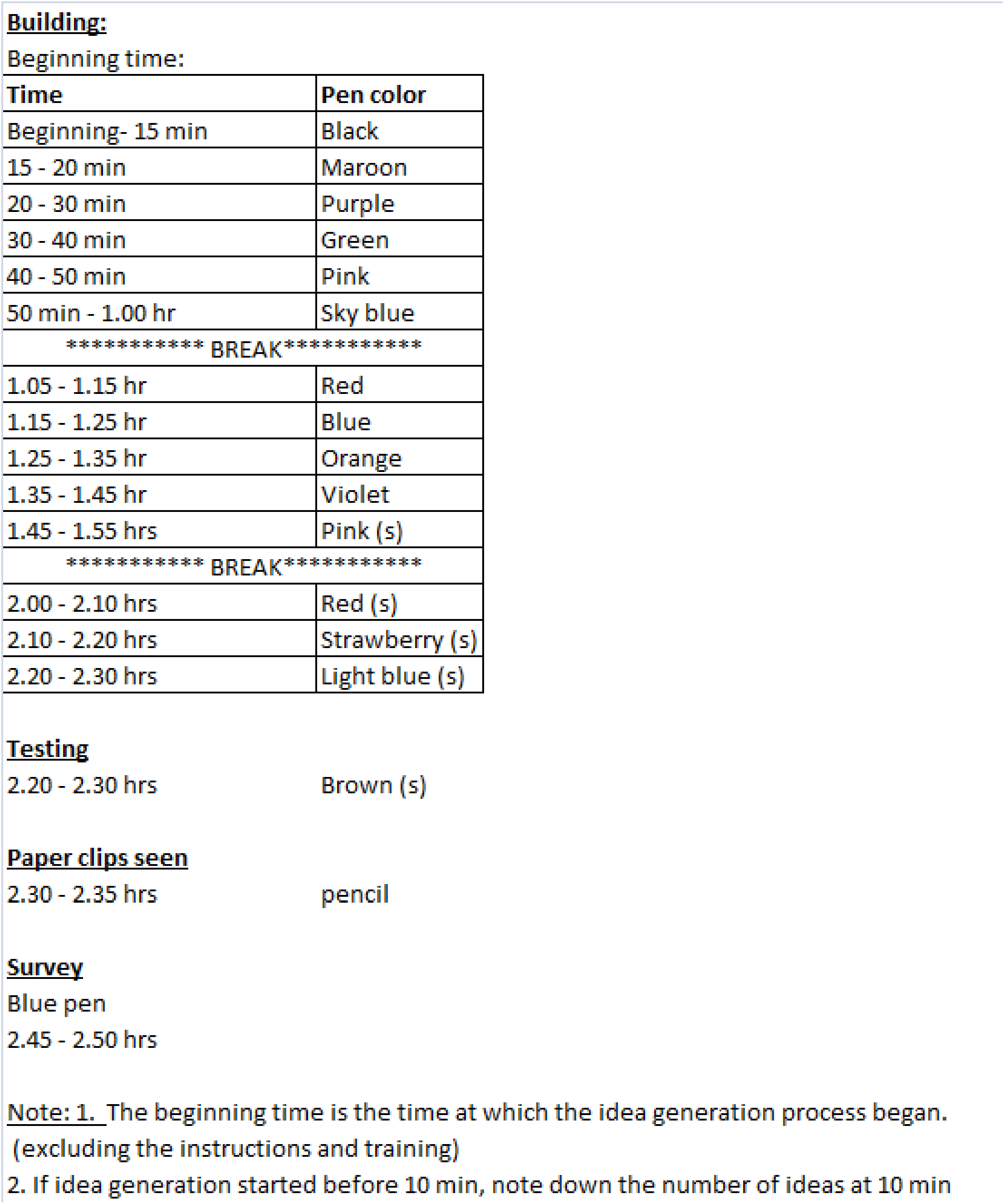
Blue pen

2.45 - 2.50 hrs

Note: 1. The beginning time is the time at which the idea generation process began. (excluding the instructions and training)

2. If idea generation started before 10 min, note down the number of ideas at 10 min

12. Timeline and Pen Change Log – Metal Building Condition



Building:

Beginning time:

Time	**Pen color**
Beginning- 15 min	Black
15 - 20 min	Maroon
20 - 30 min	Purple
30 - 40 min	Green
40 - 50 min	Pink
50 min - 1.00 hr	Sky blue
*********** BREAK***********	
1.05 - 1.15 hr	Red
1.15 - 1.25 hr	Blue
1.25 - 1.35 hr	Orange
1.35 - 1.45 hr	Violet
1.45 - 1.55 hrs	Pink (s)
*********** BREAK***********	
2.00 - 2.10 hrs	Red (s)
2.10 - 2.20 hrs	Strawberry (s)
2.20 - 2.30 hrs	Light blue (s)

Testing

2.20 - 2.30 hrs	Brown (s)

Paper clips seen

2.30 - 2.35 hrs	pencil

Survey

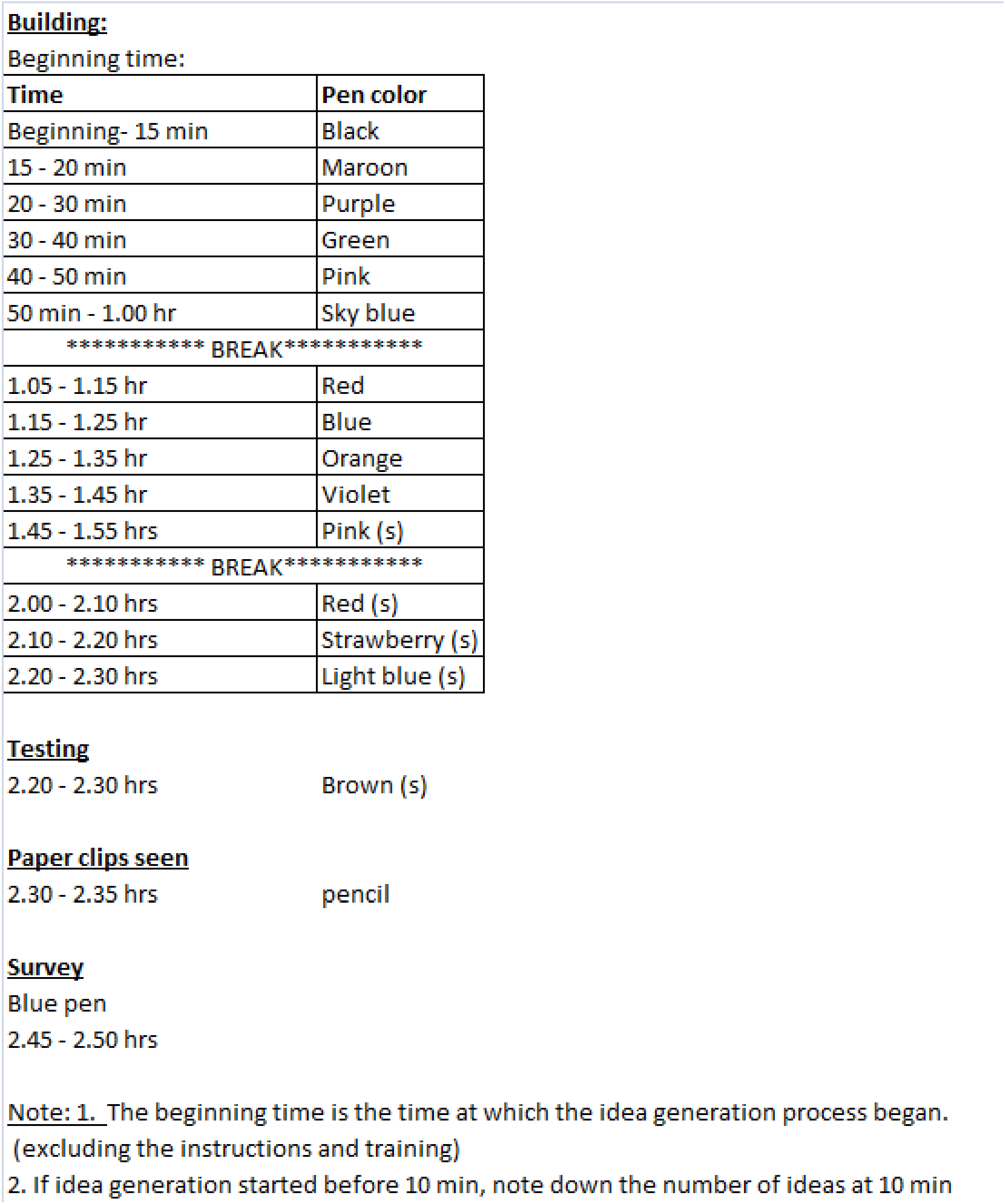
Blue pen

2.45 - 2.50 hrs

Note: 1. The beginning time is the time at which the idea generation process began. (excluding the instructions and training)

2. If idea generation started before 10 min, note down the number of ideas at 10 min

13. Timeline and Pen Change Log – Plastic Building Condition



Building:

Beginning time:

Time	Pen color
Beginning- 15 min	Black
15 - 20 min	Maroon
20 - 30 min	Purple
30 - 40 min	Green
40 - 50 min	Pink
50 min - 1.00 hr	Sky blue
*********** BREAK***********	
1.05 - 1.15 hr	Red
1.15 - 1.25 hr	Blue
1.25 - 1.35 hr	Orange
1.35 - 1.45 hr	Violet
1.45 - 1.55 hrs	Pink (s)
*********** BREAK***********	
2.00 - 2.10 hrs	Red (s)
2.10 - 2.20 hrs	Strawberry (s)
2.20 - 2.30 hrs	Light blue (s)

Testing

2.20 - 2.30 hrs	Brown (s)

Paper clips seen

2.30 - 2.35 hrs	pencil

Survey

Blue pen

2.45 - 2.50 hrs

Note: 1. The beginning time is the time at which the idea generation process began. (excluding the instructions and training)

2. If idea generation started before 10 min, note down the number of ideas at 10 min

14. Timeline and Pen Change Log – Metal Constrained Sketching Condition

Sketching:

Beginning time:

Time	Pen color
Beginning- 15 min	Black
15 - 20 min	Maroon
20 - 30 min	Purple
30 - 40 min	Green
40 - 50 min	Pink
50 min - 1.00 hr	Sky blue
*********** BREAK***********	
1.05 - 1.15 hr	Red
1.15 - 1.25 hr	Blue
1.25 - 1.35 hr	Orange
1.35 - 1.45 hr	Violet
***********BREAK***********	

Building

Beginning time:

Time	Pen color
Beginning - 2.00 hrs	Pink (s)
2.00 - 2.10 hrs	Red (s)
2.10 - 2.20 hrs	Strawberry (s)
2.20 - 2.30 hrs	Light blue (s)

Testing

2.30 - 2.40 hrs Brown (s)

Paper clips seen

2.40 - 2.45 hrs pencil

Survey

Blue pen

2.45 - 2.50 hrs

Note: 1. The beginning time is the time at which the idea generation process began.
(excluding the instructions and training)
2. If idea generation started before 10 min, note down the number of ideas at 10 min

15. Timeline and Pen Change Log – Plastic Constrained Sketching Condition

Sketching:

Beginning time:

Time	Pen color
Beginning- 15 min	Black
15 - 20 min	Maroon
20 - 30 min	Purple
30 - 40 min	Green
40 - 50 min	Pink
50 min - 1.00 hr	Sky blue
*********** BREAK***********	
1.05 - 1.15 hr	Red
1.15 - 1.25 hr	Blue
1.25 - 1.35 hr	Orange
1.35 - 1.45 hr	Violet
***********BREAK***********	

Building

Beginning time:

Time	Pen color
Beginning - 2.00 hrs	Pink (s)
2.00 - 2.10 hrs	Red (s)
2.10 - 2.20 hrs	Strawberry (s)
2.20 - 2.30 hrs	Light blue (s)

Testing

2.30 - 2.40 hrs Brown (s)

Paper clips seen

2.40 - 2.45 hrs pencil

Survey

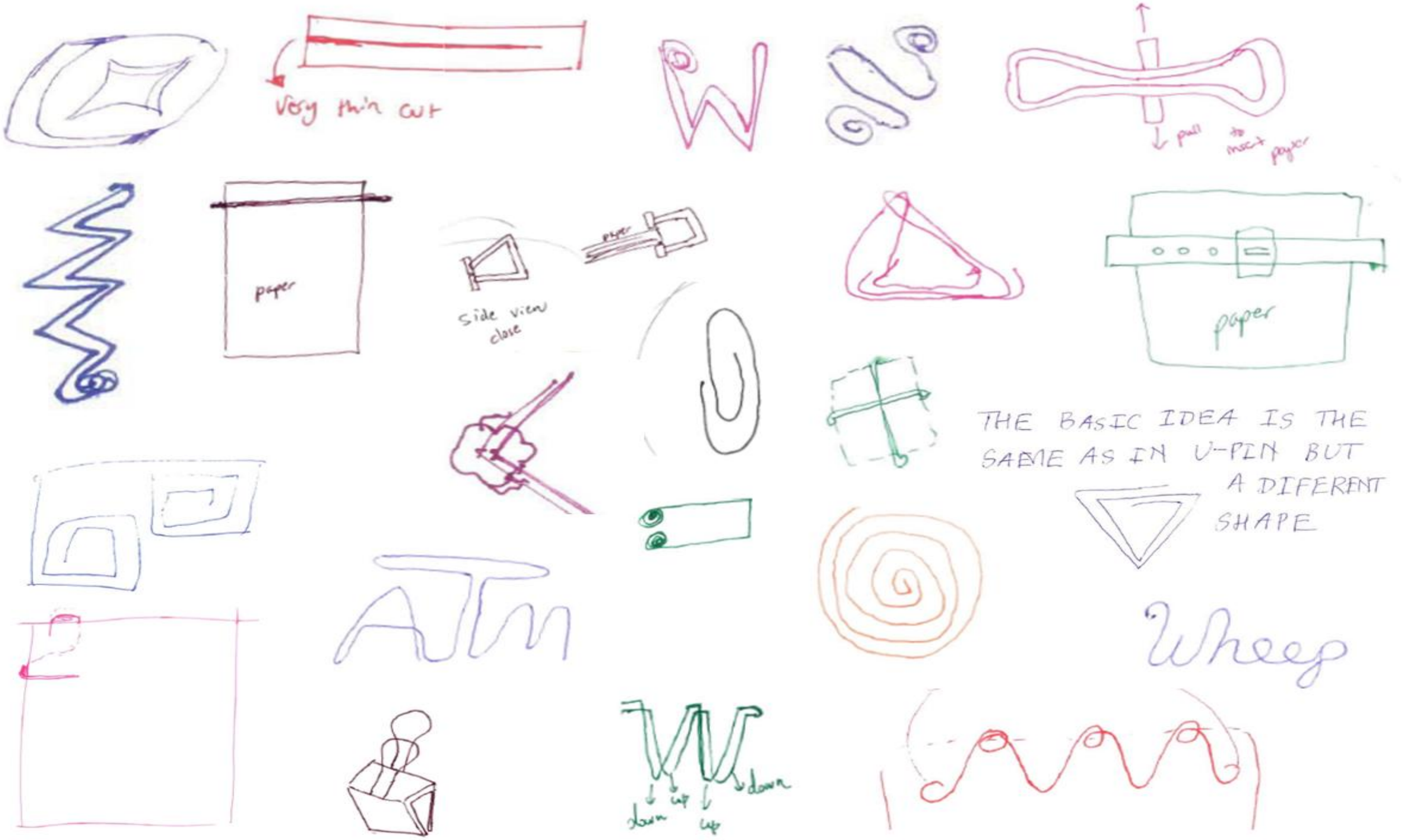
Blue pen

2.45 - 2.50 hrs

Note: 1. The beginning time is the time at which the idea generation process began. (excluding the instructions and training)

2. If idea generation started before 10 min, note down the number of ideas at 10 min

16. Example Solutions Created by Participants

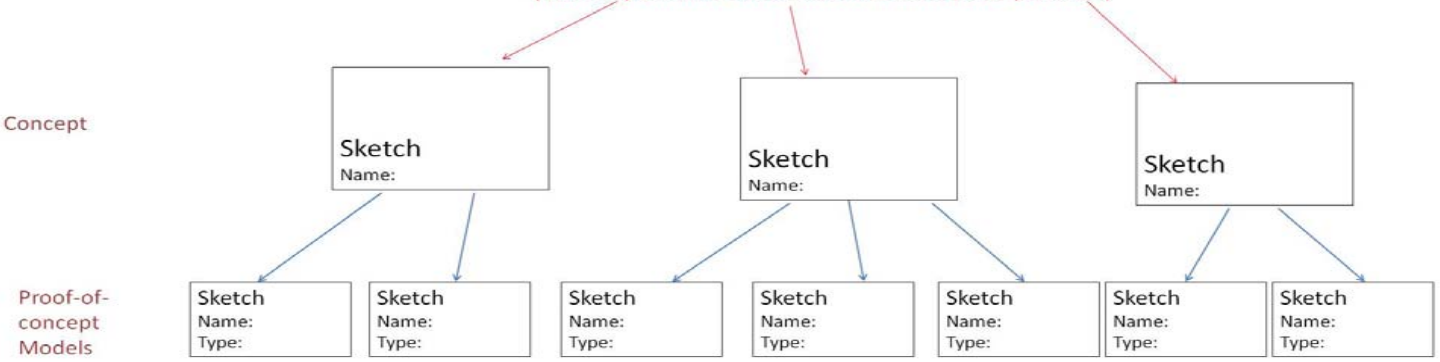


APPENDIX C

MATERIALS USED FOR QUALITATIVE STUDIES ON GRADUATE DESIGN TEAMS AND INNOVATIVE PRODUCT CASES

1. <u>Prototyping Planning Sheets Provided to Graduate Design Teams</u>

Proof-of-concept planning template
One excel spreadsheet is required for each concept
(You may include hand sketches instead of pictures)

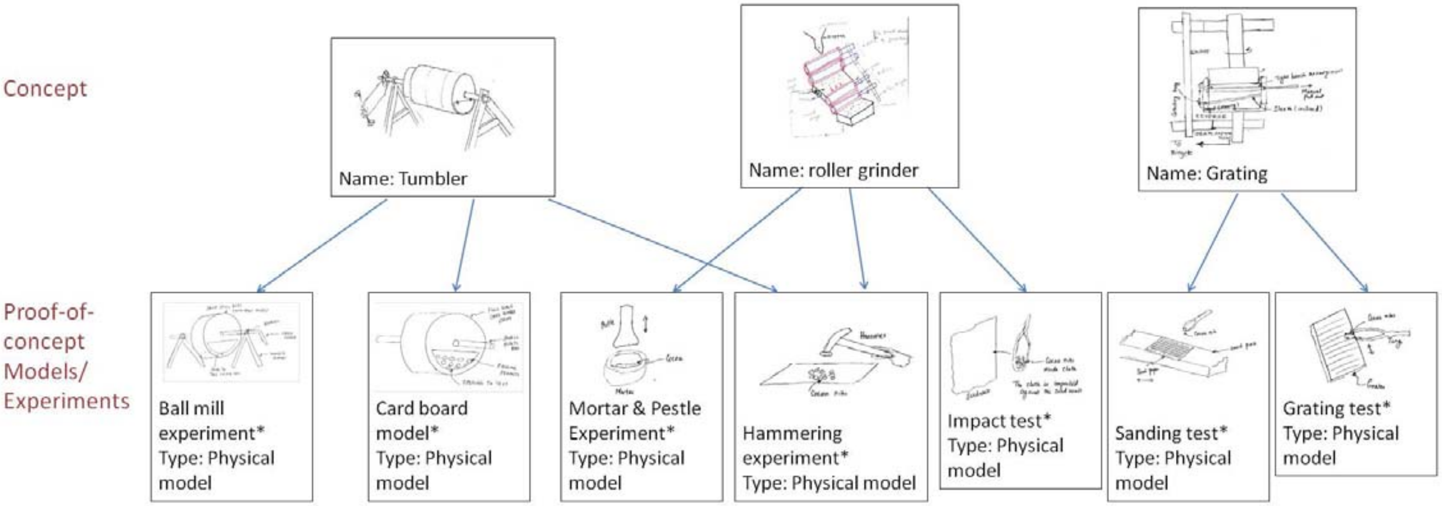


This is a template only. Modify according to your requirements

Proof-of-concept planning template

One excel spreadsheet is required for each concept

(You may include hand sketches instead of pictures)



Concept

Name: Tumbler

Name: roller grinder

Name: Grating

Proof-of-concept Models/ Experiments

Ball mill experiment*
Type: Physical model

Card board model*
Type: Physical model

Mortar & Pestle Experiment*
Type: Physical model

Hammering experiment*
Type: Physical model

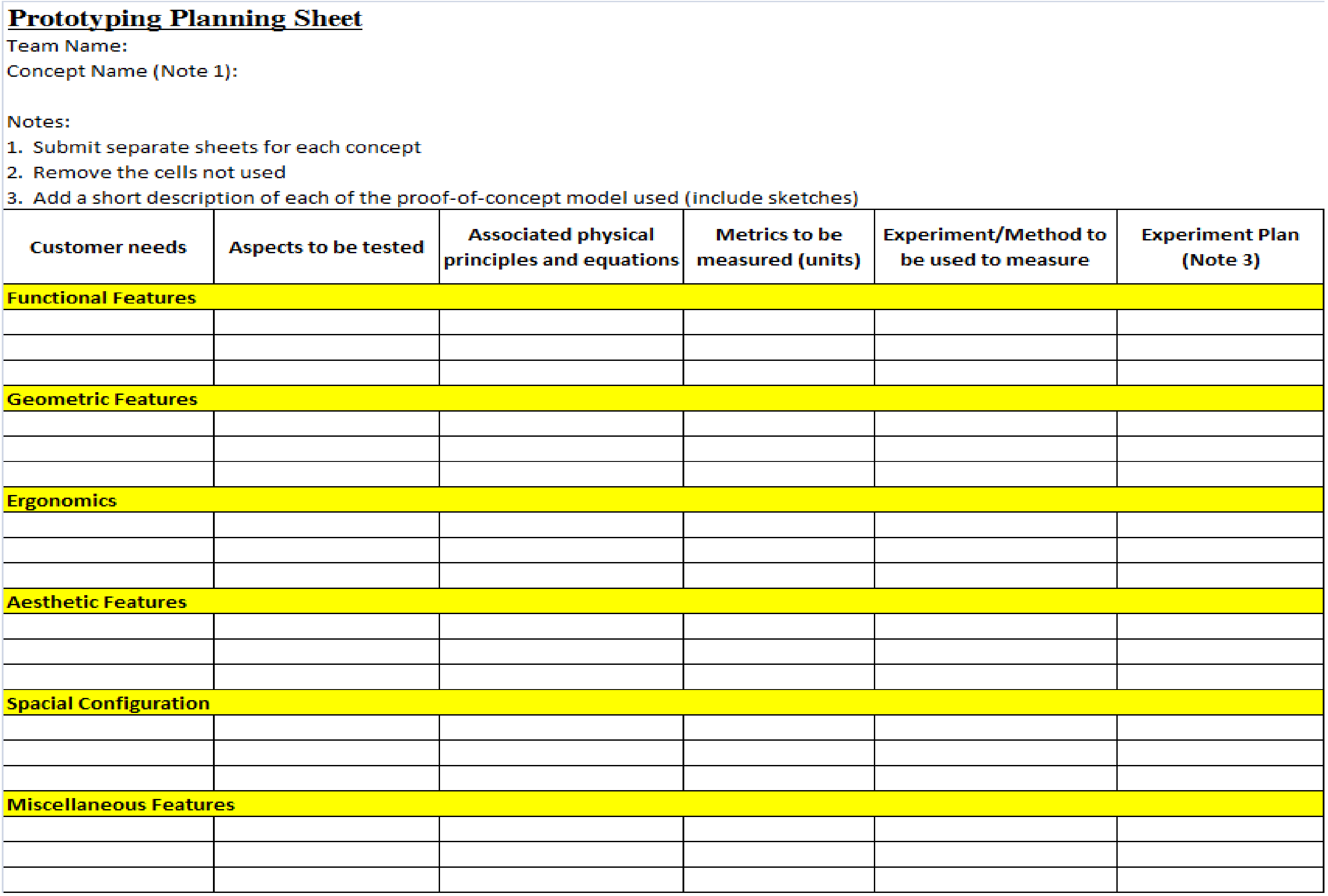
Impact test*
Type: Physical model

Sanding test*
Type: Physical model

Grating test*
Type: Physical model

* The details of all the proof-of-concept experiments need to be included in the progress report

2. Prototyping Planning Template and Examples Provided to Graduate Design Teams



Prototyping Planning Sheet

Team Name:

Concept Name (Note 1):

Notes:

1. Submit separate sheets for each concept
2. Remove the cells not used
3. Add a short description of each of the proof-of-concept model used (include sketches)

Customer needs	Aspects to be tested	Associated physical principles and equations	Metrics to be measured (units)	Experiment/Method to be used to measure	Experiment Plan (Note 3)
Functional Features					
Geometric Features					
Ergonomics					
Aesthetic Features					
Spacial Configuration					
Miscellaneous Features					

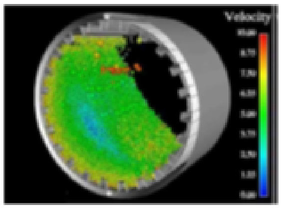
Guidelines to fill prototype planning sheet

Example:

Cocoa grinding machine

Problem statement: To design a machine to grind cocoa nibs to sizes not detectable by human tongue

Concept: Ball mill



Step 1: List all the customer needs for the design problem

eg: Grind the cocoa nibs to sizes not detectable by human tongue
Easy to operate
Should not use electricity

Step 2: For each customer need, list down what associated aspects need to be tested

eg: ***Customer need:***
Grind the cocoa nibs to sizes not detectable by human tongue
Features to be tested:
Powdering action
Rotaional speed
Number and sizes of the balls reqired

Step 3: For each feature to be tested, list the associated physical principle or the equations required

eg: Feature: Powdering action
Physical principle: Impact force
Feature: Number and sizes of the balls reqired
Equation: $B = \sqrt{\frac{F\,W_i}{K\,C_s}}\;\sqrt{S}\;/\;\sqrt{D}$ [1]

Step 4: List down the metric to be used to measure the feature

eg: Feature: Powdering action
Metric: Size of particles in the powder (in microns)
Feature: Number and sizes of the balls reqired
Metric : Number and sizes of balls required(Number, mm)

Step 5: List the experiment/method to be used to measure the metric

eg: Metric: Size of particles in the powder (in microns)
Method: Measure the particle size using non-contact profilometer
Metric : Number and sizes of balls required(Number, mm)
Method: By using the equation and trail and error

Step 6: Give a brieff description on how you are planning to measure the metric from the specified experiment/method

1. Include a description of each of your proof-of-concept model in a separate sheet.
2. Include sketches with the description
3. Show the links between your concepts and proof-of-concepts in the proof-of concept planning template

Use these data to fill in the table as shown in the example planning sheet

Prototyping Planning Sheet: Example 1

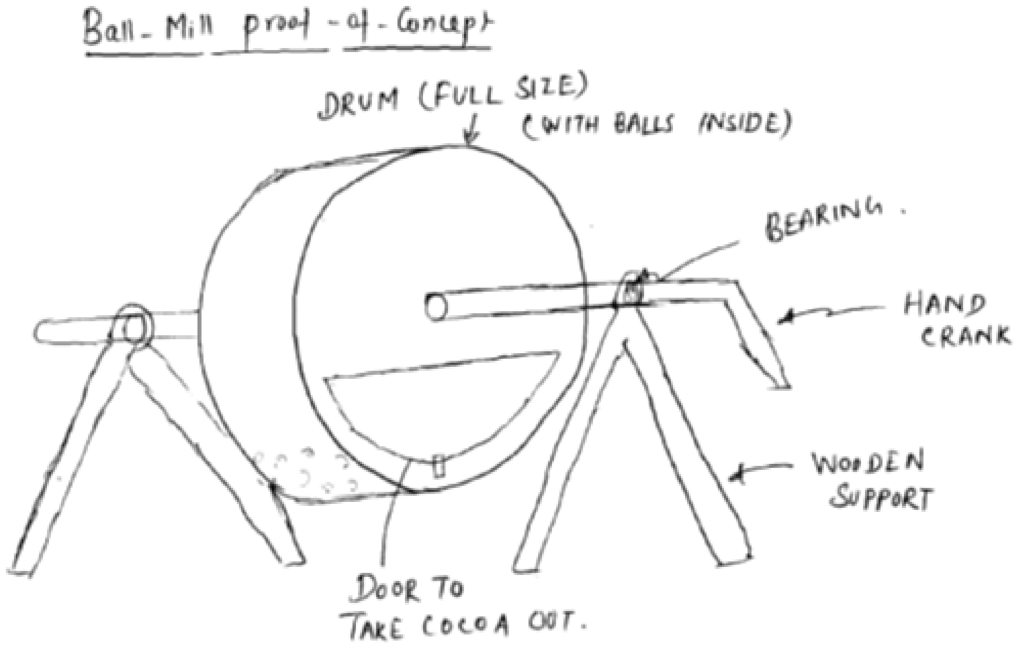
Team Name: Cocoa Ninjas

Concept Name (Note 1): Ball Mill

Notes:
1. Submit separate sheets for each concept
2. Remove the cells not used
3. Add a short description of each of the proof-of-concept model used (include sketches)

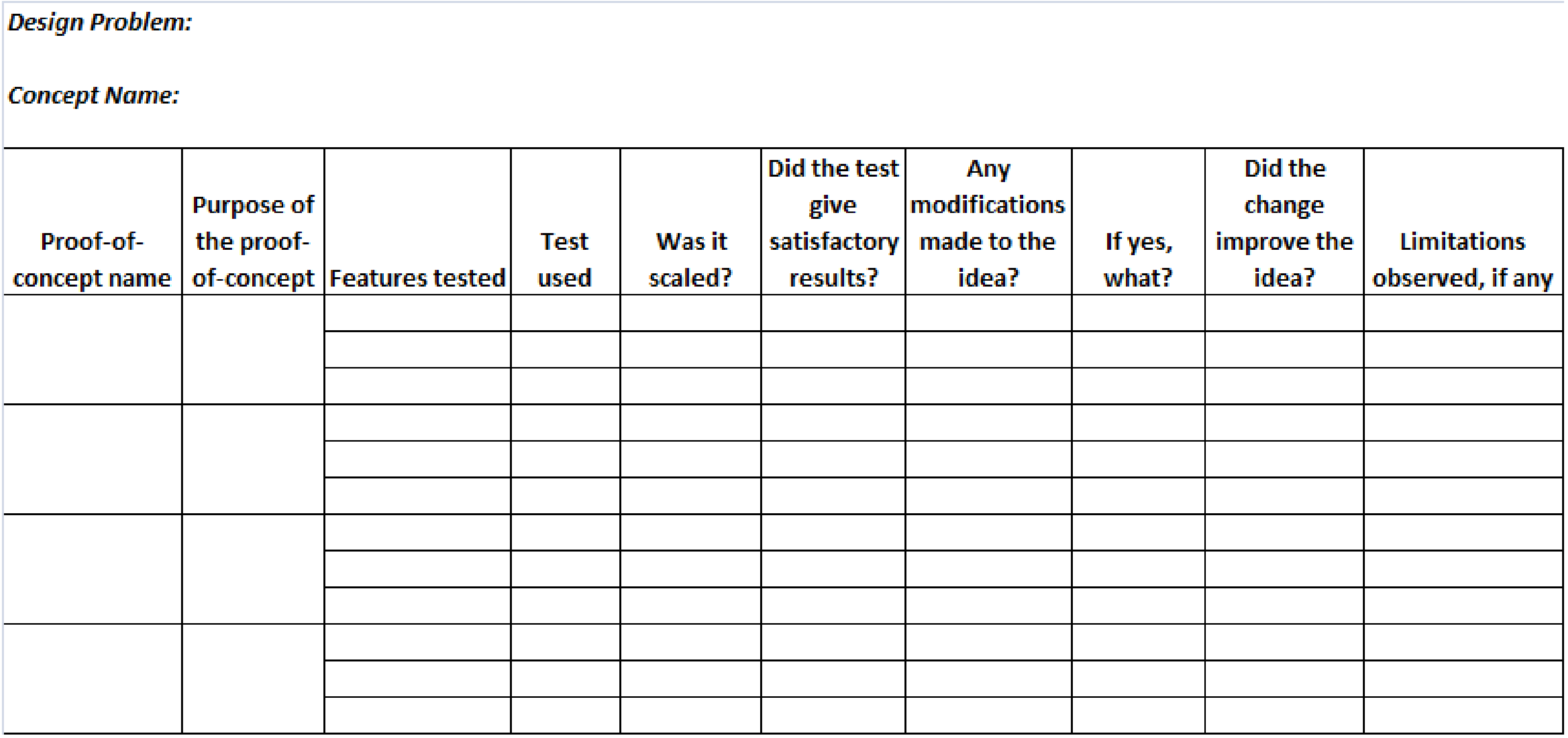
Customer needs	Aspects to be tested	Associated physical principles and equations	Metrics to be measured (units)	Experiment/Method to be used to measure	Experiment Plan (Note 3)
Functional Features					
The particle should not be detectable by tongue	Powdering action	Impact force	Size of particles in the powder (in microns)	Ball mill experiment	Measure the particle size using non-contact profilometer
	Ideal rotational speed	Rotational speed should be optimum so that the impact force is sufficient to powder cocoa	Speed of rotation (rpm)	Ball mill experiment	Do multiple runs and determine the speed at which the required particle size can be obtained
	Number and sizes of balls required	$B = \sqrt{\frac{F\, Wi}{K\, Cs}}\ \sqrt{S} \Big/ \sqrt{D}$ [1]	Number and sizes of balls required(Number, mm)	Ball mill experiment	Do multiple runs varying the number and sizes of the balls and determine those required for the required particle size
The device should not work on electrical energy	Energy source - human	Conversion of human/animal energy to mechanical energy	Energy (torque*speed)	Ball mill experiment	Do multiple runs and determine the optimum speed and torque required to operate the model
Ergonomics					
Cocoa powder should be removable very easily	Ease to remove cocoa powder	the access door should be easy to open and close	Configuration of the door	Card board model	Try various configurations of doors in the card board model and determine the optimum one

Proof-of concept name: Ball Mill



This is a full scale model to test the rotational speed required, efficiency of powdering action, number and sizes of the balls required and the dimensions required for the drum. The drum is made of steel and it is supported at 1 feet elevation from the ground using two supports. The drum is rotated using a hand crank. The steel balls are loaded inside the drum. The cocoa nibs are fed through the door. When the drum rotates, the balls fall on the nibs and due to the impact they get powdered.

3. Template Used by Graduate Teams to Report Changes during Prototyping



Design Problem:

Concept Name:

Proof-of-concept name	Purpose of the proof-of-concept	Features tested	Test used	Was it scaled?	Did the test give satisfactory results?	Any modifications made to the idea?	If yes, what?	Did the change improve the idea?	Limitations observed, if any

APPENDIX D

EXPERIMENT MATERIALS AND EXAMPLE DATA FROM THE STUNT CAR EXPERIMENT

1. Technical Memo Provided to Students – Effective Example

Memorandum

To: Engineering Staff
ENGR 111 – Design Teams

From: Natela Ostrovskaya
Technical Director

Subject: Project #2 – Design & Testing of a Stunt Vehicle

Purpose and Background:

The Texas Transportation Institute (a research agency under the Texas A&M University System) has an extensive highway safety research program involving the interaction between vehicles and the hardware (signs, bridge abutments, etc.) along the side of the road. An important aspect of this research concerns the prediction of vehicle behavior using mathematical modeling based upon extensive experimental data and basic physics. A number of civil and mechanical engineering professors at TAMU were the Principle Investigators in this effort and a few of them have formed consulting firms based upon their research. Vehicle crash dynamics form the basis for: expert testimony in accident investigation, action scenes in big budget action films, design of passive restraint systems for the occupants, active crash avoidance systems, etc.

The intent of this project is not to make all of us experts in vehicle dynamics but to simply familiarize us with the basics of the physics and mathematics involved in this important field. In essence, the vehicle become a projectile the moment in leaves the ramp and launches into the air. The mathematics and physics of this behavior are well understood and our task is to design the "optimum" stunt vehicle using the materials at hand taking this knowledge into account. A brief project description follows.

PROJECT DESCRIPTION:

Your task is to design and fabricate a stunt vehicle that will be launched from a ramp as a projectile with a known velocity (see Fig. 1). While the vehicle traverses down the ramp, it should gain enough launch speed to travel a horizontal distance D before it lands: D ≥ 100 cm. The vehicle must be able to survive (remain in one piece) the entire trip from the top of the ramp, through the two (target) bill boards and until it comes to a complete stop after landing on the floor.

In order to fit on the ramp, the wheel base should be between 13 and 18 cm wide or 4 cm if using a single ramp. In order to be traveling horizontally at launch, the wheel base must be no more than 15 cm long. The target (see Fig. 3) for the speed measuring device must be 2.35 cm (3 Lego beams) wide, extend above the vehicle by at least 2 cm and some part of the target area must be 11 cm above the ramp. Thus, the vehicle must be no taller than 9 cm. There are no other restrictions on the design of the vehicle.

The shape and height of the ramp is known (see the Fig. 1 and Fig. 2). At the moment of takeoff the velocity vector of the vehicle is approximately horizontal. We have measuring equipment (Photogate) to experimentally determine the velocity of the vehicle as it leaves the lower end of the ramp (denoted as v_0 on Fig. 1).

The billboards will be positioned at distances D1 and D2 from the ramp: D1 = 50 cm, D2 = 70 cm. The billboards will be provided. For your calculations, assume that the center of the car passes through the center of each billboard frame. You will have to use numerical analysis to determine the vertical positions H1 and H2 for the centers of the billboard frames. The height of each billboard frame (that is, the gap) should not exceed the greater of (a) the length the vehicle times the safety coefficient (e.g. 1.2) or (b) the height of your vehicle (including the Photogate target) times the safety coefficient. The safety coefficient should not exceed 1.5.

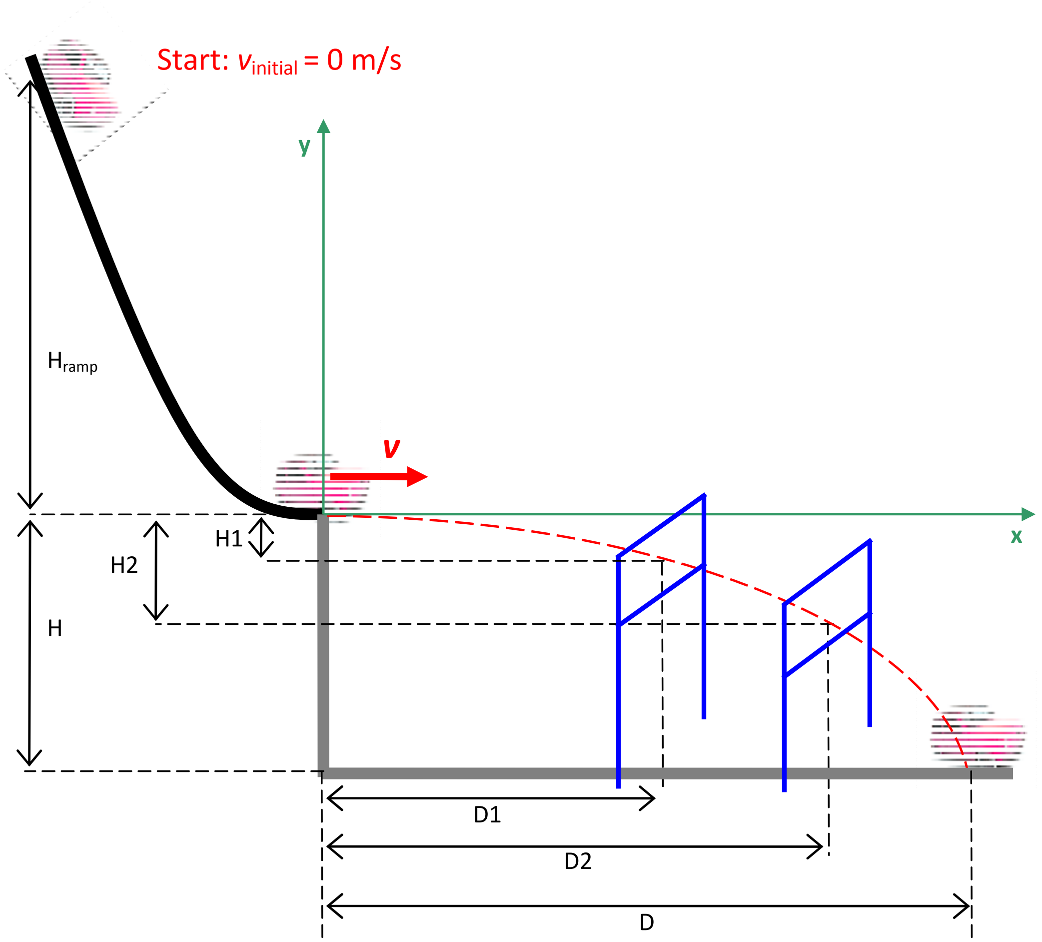


Figure 1. Sketch of the Stunt.

Note: measure H_{ramp} and H once the ramps are installed in the classrooms.

Deliverables:

1. Rolling chassis built from Lego parts.
2. Technical Memorandum with the following topics at a minimum:
    a. Purpose and scope of the project
    b. Technical Approach – a description of project activities and how/why you did them
    c. Data collection and analysis
        i. Table of original data
        ii. Analysis
    d. Results: Actual and Theoretical Speeds
        i. Actual Measured Speed
        ii. Calculated Speeds
        iii. Comparison
    e. Conclusions and Recommendations

Evaluation Criteria:

1. Conformance to physical specifications with respect to height, length, wheel base. Weight 30%
2. Conformance to performance specifications with respect to targets, launch distance, survivability, etc. This will be based upon the best 2 out of 3 trials. Weight 45%
3. Correlation between calculated and actual values based upon the technical memos. Weight15%
4. Style points Weight 10%

Work Breakdown Structure and Schedule (tentative, subject to change depending upon circumstances)

Task 1

In-class CAR-1: Each team has to build two different cars (two completely different designs). Show your designs to the instructors at the end of class.

Homework: **due at the beginning of CAR-2 class (Thursday, April 7th).**

- Use PHYS-218 knowledge to
    - Determine the ideal takeoff speed v_0 in terms of given parameters (see Fig.1).
    - Determine the ideal range (horizontal distance D) your car will travel after takeoff in terms of given parameters (see Fig.1).

Ignore air resistance and energy losses due to friction.

- Prepare a brief tech memo:
  - Discuss your car designs. Include pictures of your cars.
  - Predict which car will have greater v_0 . Explain.
  - Which set of tires do you recommend to use and why?
  - How will the actual takeoff speed v_0 differ from the ideal takeoff speed? Why?
  - How will the actual range of a car differ from the ideal range? Why?
  - In Appendix: provide detailed calculations of the ideal takeoff speed v_0 and the ideal range.
  - Turn in the tech memo at the beginning of CAR-2 class. Keep the electronic version of the tech memo (and a copy of your calculations): you will be using it during CAR-2 class.

Task 2

In-class CAR-2: Test the cars on the ramp. Test each vehicle twice using different tires. Write a paragraph about:

- How do your observations (tires, range, etc.) differ from your predictions in the tech memo for Task 1?
- What changes (if any) do you have to make to your vehicle design?

Homework: **due at the beginning of CAR-3 class (Thursday, April 14th).**

- Use your notes from class (Thursday, April 7th) CAR-2 to finalize the vehicle design.
- Prepare a paragraph:
  - List and discuss the changes you made in your vehicle design.
  - Include a picture of the vehicle.

Task 3

In-class CAR-3: Study projectile motion with air resistance. Use MS Excel to perform numerical calculation to determine position of a projectile at any moment of time. Graph the trajectories of a projectile with and without air drag.

Homework: **due at the beginning of CAR-4 class (April 19th).**

- Use MS Excel to perform numerical calculation to determine vertical positions of the centers of billboard frames.
- Report your result in a brief tech memo:

  - Graph the trajectories of the vehicle with and without air drag on the same chart.
  - Save the Excel file with your calculations: you will use it in class CAR-4.

Task 4

In-class CAR-4: Perform dry run of the vehicle stunt. Use photogates to determine average takeoff speed of the vehicle (make 3 measurements). Make corrections to numerical calculations (see Task 3) as necessary.

Homework: **due at the beginning of CAR-5 class (April 26th).**

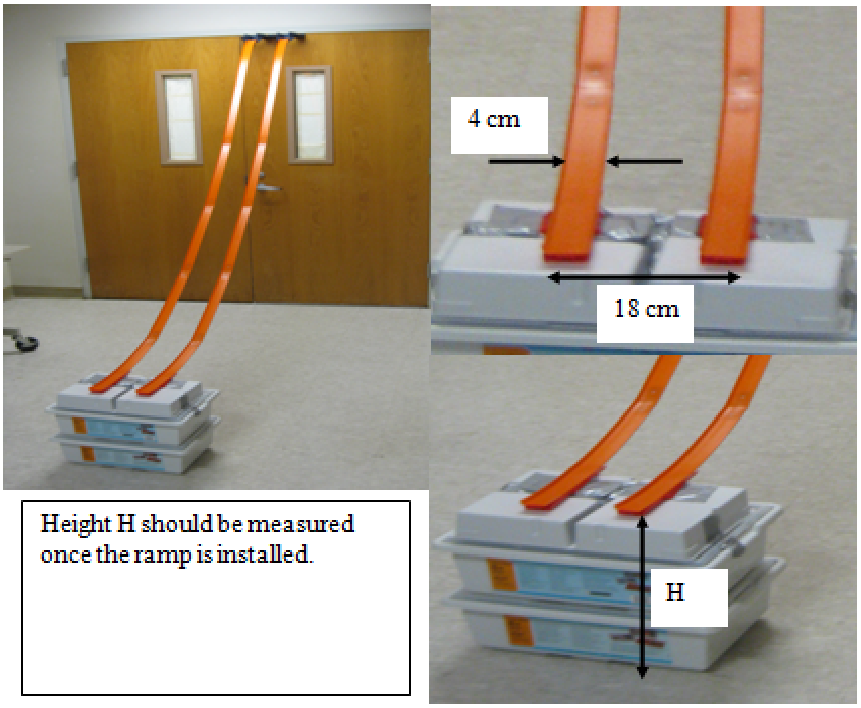
- Report your result in a paragraph.
  - Use Statistics.

Task 5

In-class CAR-5: Demonstrate the vehicle stunt for a grade. Extra-credit: add one more billboard frame.

Homework: **due in one week.**

- Calculate the cost of the car: take the car apart and organize in piles of similar parts (straight bars beams, tires, rods, connectors, etc.). The calculated cost is a function of material cost plus design cost and fabrication cost. The material cost is the total weight of the parts in grams times 100. The design cost is the total number of parts (less the connectors) times 25. The fabrication cost is 20-times the number of connectors. (This is subject to change.)
- Prepare final report (tech memo). Include all stages of the stunt vehicle design process.



Height H should be measured once the ramp is installed.

Fig. 2: Preliminary Pictures of Actual Test Track

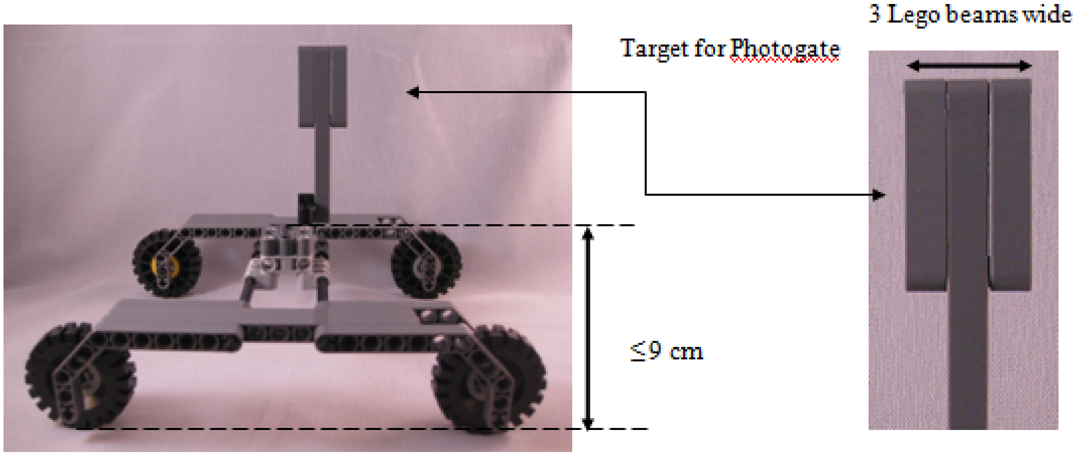


Fig. 3: Example of a Vehicle. Do not include the brick or any sensors. Target placement is very important; so, be careful!

2. Technical Memo Provided to Students – Flawed Example

Memorandum

To:	Engineering Staff ENGR 111 – Design Teams
From:	Natela Ostrovskaya Technical Director
Subject:	Project #2 – Design & Testing of a Stunt Vehicle

Purpose and Background:

The Texas Transportation Institute (a research agency under the Texas A&M University System) has an extensive highway safety research program involving the interaction between vehicles and the hardware (signs, bridge abutments, etc.) along the side of the road. An important aspect of this research concerns the prediction of vehicle behavior using mathematical modeling based upon extensive experimental data and basic physics. A number of civil and mechanical engineering professors at TAMU were the Principle Investigators in this effort and a few of them have formed consulting firms based upon their research. Vehicle crash dynamics form the basis for: expert testimony in accident investigation, action scenes in big budget action films, design of passive restraint systems for the occupants, active crash avoidance systems, etc.

The intent of this project is not to make all of us experts in vehicle dynamics but to simply familiarize us with the basics of the physics and mathematics involved in this important field. In essence, the vehicle become a projectile the moment in leaves the ramp and launches into the air. The mathematics and physics of this behavior are well understood and our task is to design the "optimum" stunt vehicle using the materials at hand taking this knowledge into account. A brief project description follows.

PROJECT DESCRIPTION:

Your task is to design and fabricate a stunt vehicle that will be launched from a ramp as a projectile with a known velocity (see Fig. 1). While the vehicle traverses down the ramp, it should gain enough launch speed to travel a horizontal distance D before it lands: D ≥ 100 cm. The vehicle must be able to survive (remain in one piece) the entire trip from the top of the ramp, through the two (target) bill boards and until it comes to a complete stop after landing on the floor.

In order to fit on the ramp, the wheel base should be between 13 and 18 cm wide or 4 cm if using a single ramp. In order to be traveling horizontally at launch, the wheel base must be no more than 15 cm long. The target (see Fig. 3) for the speed measuring device must be 2.35 cm (3 Lego beams) wide, extend above the vehicle by at least 2 cm and some part of the target area must be 11 cm above the ramp. Thus, the vehicle must be no taller than 9 cm. There are no other restrictions on the design of the vehicle.

The shape and height of the ramp is known (see the Fig. 1 and Fig. 2). At the moment of takeoff the velocity vector of the vehicle is approximately horizontal. We have measuring equipment (Photogate) to experimentally determine the velocity of the vehicle as it leaves the lower end of the ramp (denoted as v_0 on Fig. 1).

The billboards will be positioned at distances D1 and D2 from the ramp: D1 = 50 cm, D2 = 70 cm. The billboards will be provided. For your calculations, assume that the center of the car passes through the center of each billboard frame. You will have to use numerical analysis to determine the vertical positions H1 and H2 for the centers of the billboard frames. The height of each billboard frame (that is, the gap) should not exceed the greater of (a) the length the vehicle times the safety coefficient (e.g. 1.2) or (b) the height of your vehicle (including the Photogate target) times the safety coefficient. The safety coefficient should not exceed 1.5.

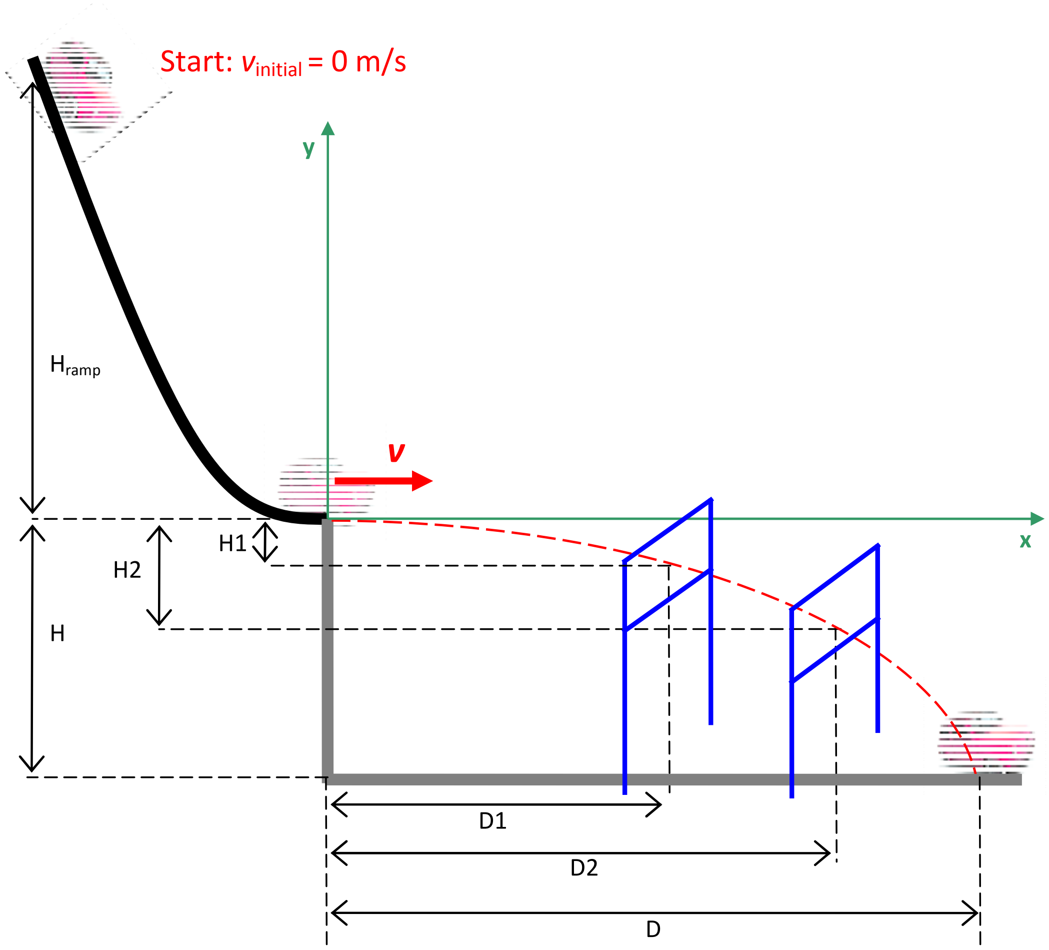


Figure 1. Sketch of the Stunt.

Note: measure H_{ramp} and H once the ramps are installed in the classrooms.

Deliverables:

3. Rolling chassis built from Lego parts.
4. Technical Memorandum with the following topics at a minimum:
    a. Purpose and scope of the project
    b. Technical Approach – a description of project activities and how/why you did them
    c. Data collection and analysis
        i. Table of original data
        ii. Analysis
    d. Results: Actual and Theoretical Speeds
        i. Actual Measured Speed
        ii. Calculated Speeds
        iii. Comparison
    e. Conclusions and Recommendations

Evaluation Criteria:

5. Conformance to physical specifications with respect to height, length, wheel base. Weight 30%
6. Conformance to performance specifications with respect to targets, launch distance, survivability, etc. This will be based upon the best 2 out of 3 trials. Weight 45%
7. Correlation between calculated and actual values based upon the technical memos. Weight15%
8. Style points Weight 10%

Work Breakdown Structure and Schedule (tentative, subject to change depending upon circumstances)

Task 1

In-class CAR-1: Each team has to build two different cars (two completely different designs). Show your designs to the instructors at the end of class.

Homework: **due at the beginning of CAR-2 class (Thursday, April 7th).**

- Use PHYS-218 knowledge to
    - Determine the ideal takeoff speed v_0 in terms of given parameters (see Fig.1).
    - Determine the ideal range (horizontal distance D) your car will travel after takeoff in terms of given parameters (see Fig.1).

Ignore air resistance and energy losses due to friction.

- Prepare a brief tech memo:
  - Discuss your car designs. Include pictures of your cars.
  - Predict which car will have greater v_0 . Explain.
  - Which set of tires do you recommend to use and why?
  - How will the actual takeoff speed v_0 differ from the ideal takeoff speed? Why?
  - How will the actual range of a car differ from the ideal range? Why?
  - In Appendix: provide detailed calculations of the ideal takeoff speed v_0 and the ideal range.
  - Turn in the tech memo at the beginning of CAR-2 class. Keep the electronic version of the tech memo (and a copy of your calculations): you will be using it during CAR-2 class.

Task 2

In-class CAR-2: Test the cars on the ramp. Test each vehicle twice using different tires. Write a paragraph about:

- How do your observations (tires, range, etc.) differ from your predictions in the tech memo for Task 1?
- What changes (if any) do you have to make to your vehicle design?

Homework: **due at the beginning of CAR-3 class (Thursday, April 14th).**

- Use your notes from class (Thursday, April 7th) CAR-2 to finalize the vehicle design.
- Prepare a paragraph:
  - List and discuss the changes you made in your vehicle design.
  - Include a picture of the vehicle.

Task 3

In-class CAR-3: Study projectile motion with air resistance. Use MS Excel to perform numerical calculation to determine position of a projectile at any moment of time. Graph the trajectories of a projectile with and without air drag.

Homework: **due at the beginning of CAR-4 class (April 19th).**

- Use MS Excel to perform numerical calculation to determine vertical positions of the centers of billboard frames.
- Report your result in a brief tech memo:

    - Graph the trajectories of the vehicle with and without air drag on the same chart.
    - Save the Excel file with your calculations: you will use it in class CAR-4.

Task 4

In-class CAR-4: Perform dry run of the vehicle stunt. Use photogates to determine average takeoff speed of the vehicle (make 3 measurements). Make corrections to numerical calculations (see Task 3) as necessary.

Homework: **due at the beginning of CAR-5 class (April 26th).**

- Report your result in a paragraph.
    - Use Statistics.

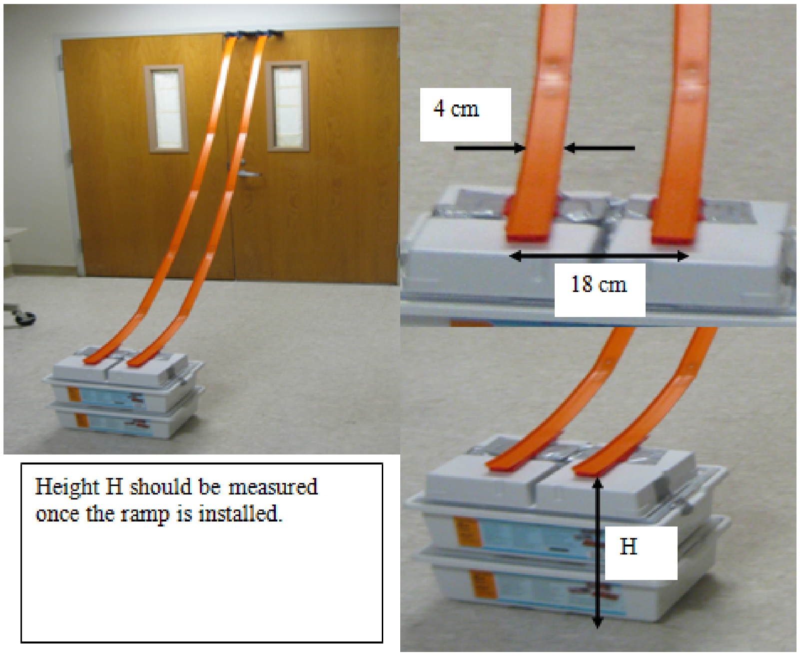
Task 5

In-class CAR-5: Demonstrate the vehicle stunt for a grade. Extra-credit: add one more billboard frame.

Homework: **due in one week.**

- Calculate the cost of the car: take the car apart and organize in piles of similar parts (straight bars beams, tires, rods, connectors, etc.). The calculated cost is a function of material cost plus design cost and fabrication cost. The material cost is the total weight of the parts in grams times 100. The design cost is the total number of parts (less the connectors) times 25. The fabrication cost is 20-times the number of connectors. (This is subject to change.)

Prepare final report (tech memo). Include all stages of the stunt vehicle design process.



Height H should be measured once the ramp is installed.

Fig. 2: Preliminary Pictures of Actual Test Track

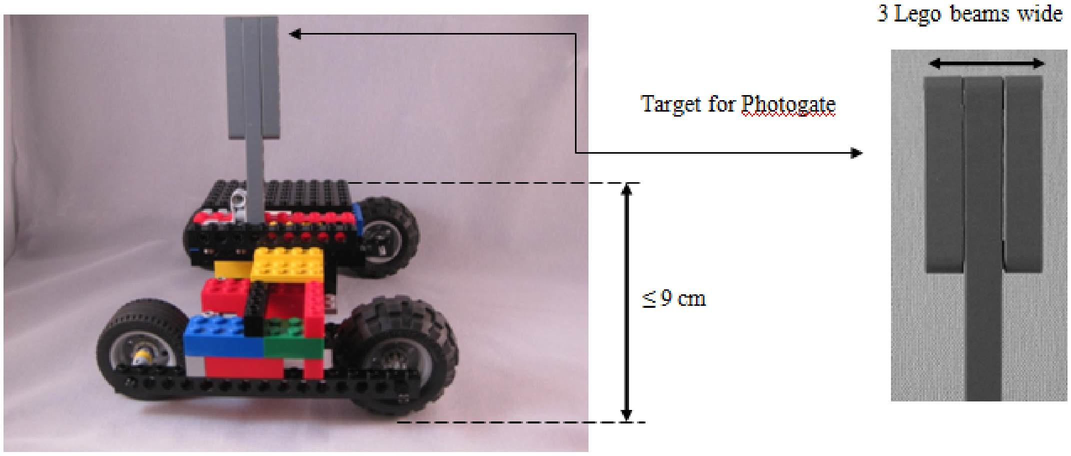


Fig. 3: Example of a Vehicle. Do not include any sensors. Target placement is very important. So be careful!

3. Technical Memo Provided to Students – Flawed Example with Warning

Memorandum

To: Engineering Staff

ENGR 111 – Design Teams

From: Natela Ostrovskaya

Technical Director

Subject: Project #2 – Design & Testing of a Stunt Vehicle

Purpose and Background:

The Texas Transportation Institute (a research agency under the Texas A&M University System) has an extensive highway safety research program involving the interaction between vehicles and the hardware (signs, bridge abutments, etc.) along the side of the road. An important aspect of this research concerns the prediction of vehicle behavior using mathematical modeling based upon extensive experimental data and basic physics. A number of civil and mechanical engineering professors at TAMU were the Principle Investigators in this effort and a few of them have formed consulting firms based upon their research. Vehicle crash dynamics form the basis for: expert testimony in accident investigation, action scenes in big budget action films, design of passive restraint systems for the occupants, active crash avoidance systems, etc.

The intent of this project is not to make all of us experts in vehicle dynamics but to simply familiarize us with the basics of the physics and mathematics involved in this important field. In essence, the vehicle become a projectile the moment in leaves the ramp and launches into the air. The mathematics and physics of this behavior are well understood and our task is to design the "optimum" stunt vehicle using the materials at hand taking this knowledge into account. A brief project description follows.

PROJECT DESCRIPTION:

Your task is to design and fabricate a stunt vehicle that will be launched from a ramp as a projectile with a known velocity (see Fig. 1). While the vehicle traverses down the ramp, it should gain enough launch speed to travel a horizontal distance D before it lands: D ≥ 100 cm. The vehicle must be able to survive (remain in one piece) the entire trip from the top of the ramp, through the two (target) bill boards and until it comes to a complete stop after landing on the floor.

In order to fit on the ramp, the wheel base should be between 13 and 18 cm wide or 4 cm if using a single ramp. In order to be traveling horizontally at launch, the wheel base must be no more than 15 cm long. The target (see Fig. 3) for the speed measuring device must be 2.35 cm (3 Lego beams) wide, extend above the vehicle by at least 2 cm and some part of the target area must be 11 cm above the ramp. Thus, the vehicle must be no taller than 9 cm. There are no other restrictions on the design of the vehicle.

The shape and height of the ramp is known (see the Fig. 1 and Fig. 2). At the moment of takeoff the velocity vector of the vehicle is approximately horizontal. We have measuring equipment (Photogate) to experimentally determine the velocity of the vehicle as it leaves the lower end of the ramp (denoted as v_0 on Fig. 1).

The billboards will be positioned at distances D1 and D2 from the ramp: D1 = 50 cm, D2 = 70 cm. The billboards will be provided. For your calculations, assume that the center of the car passes through the center of each billboard frame. You will have to use numerical analysis to determine the vertical positions H1 and H2 for the centers of the billboard frames. The height of each billboard frame (that is, the gap) should not exceed the greater of (a) the length the vehicle times the safety coefficient (e.g. 1.2) or (b) the height of your vehicle (including the Photogate target) times the safety coefficient. The safety coefficient should not exceed 1.5.

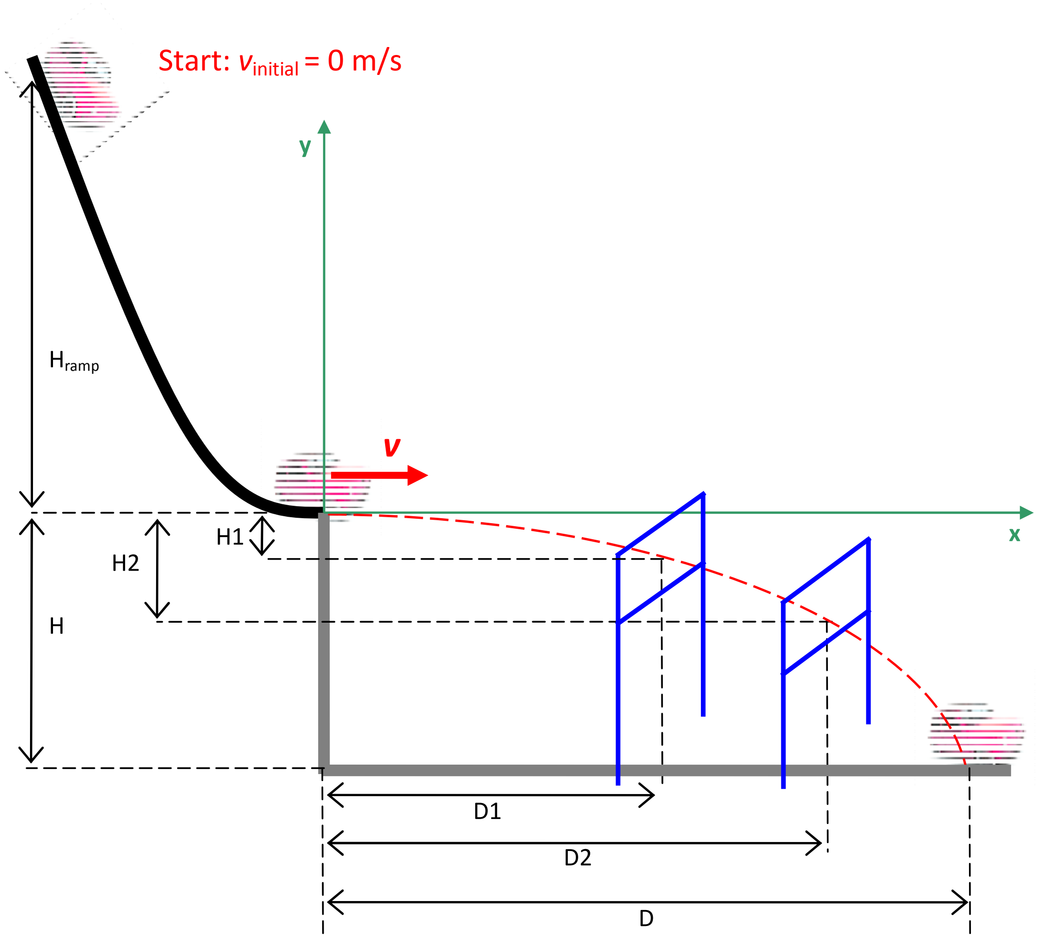


Figure 1. Sketch of the Stunt.

Note: measure H_{ramp} and H once the ramps are installed in the classrooms.

Deliverables:

5. Rolling chassis built from Lego parts.
6. Technical Memorandum with the following topics at a minimum:
    a. Purpose and scope of the project
    b. Technical Approach – a description of project activities and how/why you did them
    c. Data collection and analysis
        i. Table of original data
        ii. Analysis
    d. Results: Actual and Theoretical Speeds
        i. Actual Measured Speed
        ii. Calculated Speeds
        iii. Comparison
    e. Conclusions and Recommendations

Evaluation Criteria:

9. Conformance to physical specifications with respect to height, length, wheel base. Weight 30%
10. Conformance to performance specifications with respect to targets, launch distance, survivability, etc. This will be based upon the best 2 out of 3 trials. Weight 45%
11. Correlation between calculated and actual values based upon the technical memos. Weight15%
12. Style points Weight 10%

Work Breakdown Structure and Schedule (tentative, subject to change depending upon circumstances)

Task 1

In-class CAR-1: Each team has to build two different cars (two completely different designs). Show your designs to the instructors at the end of class.

Homework: **due at the beginning of CAR-2 class (Thursday, April 7th).**

- Use PHYS-218 knowledge to
    - Determine the ideal takeoff speed v_0 in terms of given parameters (see Fig.1).
    - Determine the ideal range (horizontal distance D) your car will travel after takeoff in terms of given parameters (see Fig.1).

Ignore air resistance and energy losses due to friction.

- Prepare a brief tech memo:
    - Discuss your car designs. Include pictures of your cars.
    - Predict which car will have greater v_0 . Explain.
    - Which set of tires do you recommend to use and why?
    - How will the actual takeoff speed v_0 differ from the ideal takeoff speed? Why?
    - How will the actual range of a car differ from the ideal range? Why?
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    - Turn in the tech memo at the beginning of CAR-2 class. Keep the electronic version of the tech memo (and a copy of your calculations): you will be using it during CAR-2 class.

Task 2

In-class CAR-2: Test the cars on the ramp. Test each vehicle twice using different tires. Write a paragraph about:

- How do your observations (tires, range, etc.) differ from your predictions in the tech memo for Task 1?
- What changes (if any) do you have to make to your vehicle design?

Homework: **due at the beginning of CAR-3 class (Thursday, April 14th).**

- Use your notes from class (Thursday, April 7th) CAR-2 to finalize the vehicle design.
- Prepare a paragraph:
    - List and discuss the changes you made in your vehicle design.
    - Include a picture of the vehicle.

Task 3

In-class CAR-3: Study projectile motion with air resistance. Use MS Excel to perform numerical calculation to determine position of a projectile at any moment of time. Graph the trajectories of a projectile with and without air drag.

Homework: **due at the beginning of CAR-4 class (April 19th).**

- Use MS Excel to perform numerical calculation to determine vertical positions of the centers of billboard frames.
- Report your result in a brief tech memo:

    - Graph the trajectories of the vehicle with and without air drag on the same chart.
    - Save the Excel file with your calculations: you will use it in class CAR-4.

Task 4

In-class CAR-4: Perform dry run of the vehicle stunt. Use photogates to determine average takeoff speed of the vehicle (make 3 measurements). Make corrections to numerical calculations (see Task 3) as necessary.

Homework: **due at the beginning of CAR-5 class (April 26th).**

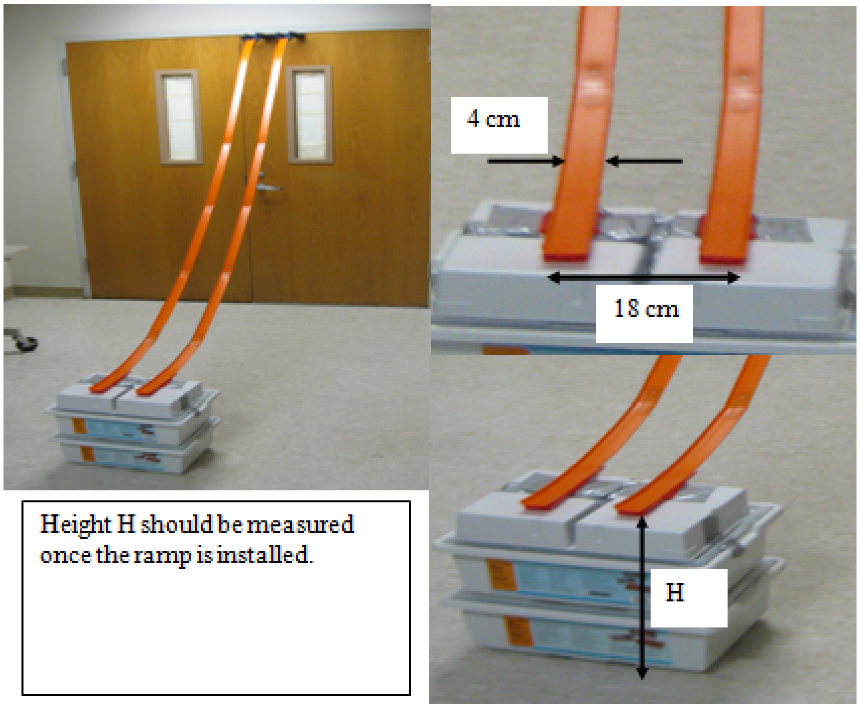
- Report your result in a paragraph.
    - Use Statistics.

Task 5

In-class CAR-5: Demonstrate the vehicle stunt for a grade. Extra-credit: add one more billboard frame.

Homework: **due in one week.**

- Calculate the cost of the car: take the car apart and organize in piles of similar parts (straight bars beams, tires, rods, connectors, etc.). The calculated cost is a function of material cost plus design cost and fabrication cost. The material cost is the total weight of the parts in grams times 100. The design cost is the total number of parts (less the connectors) times 25. The fabrication cost is 20-times the number of connectors. (This is subject to change.)
- Prepare final report (tech memo). Include all stages of the stunt vehicle design process.



Height H should be measured once the ramp is installed.

Fig. 2: Preliminary Pictures of Actual Test Track

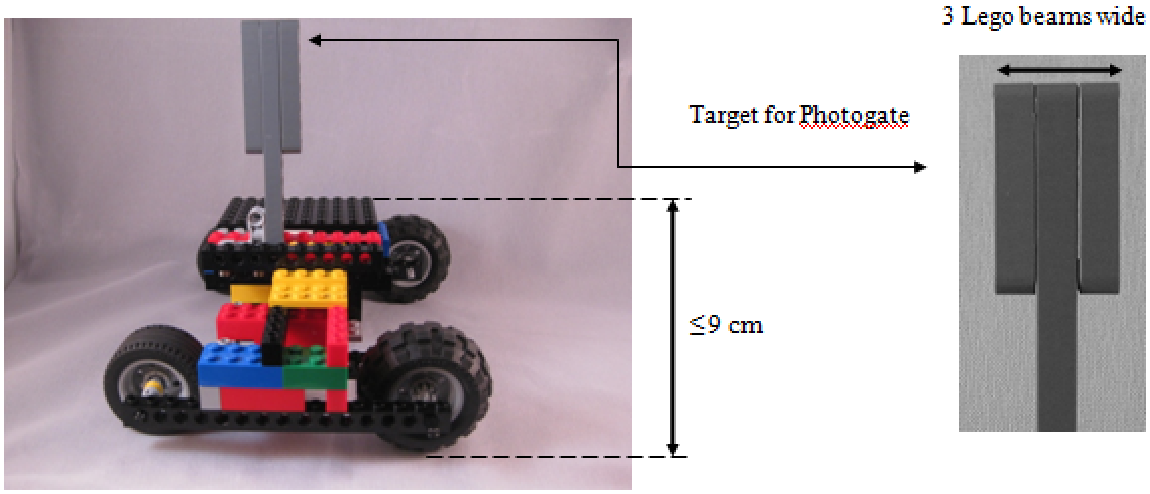
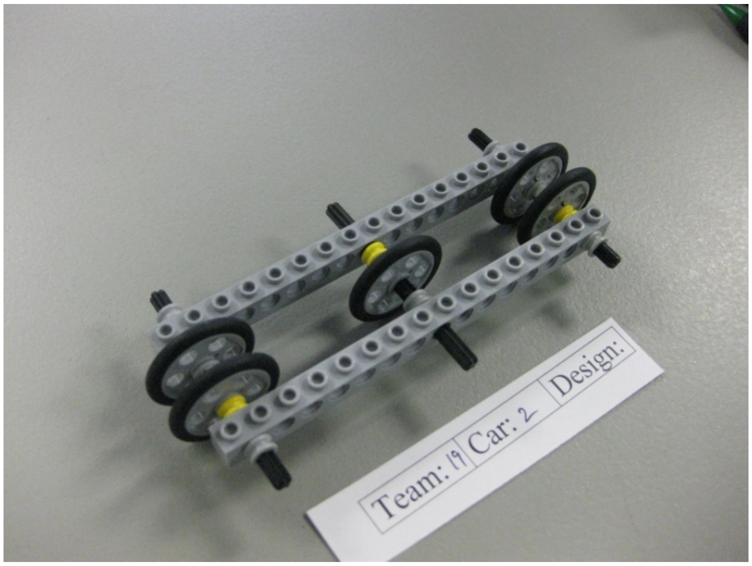
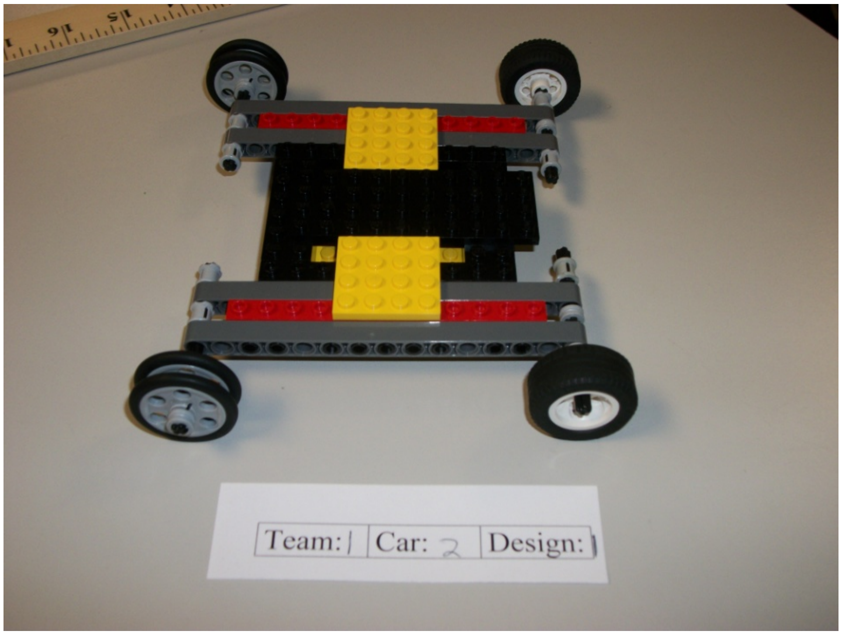
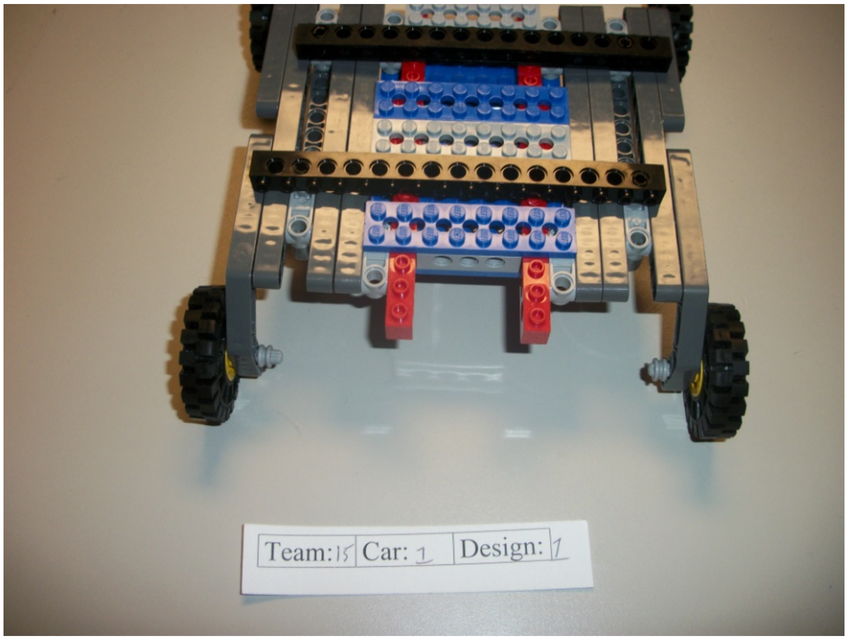


Fig. 3: Example of a Vehicle. Note that this is a bad example as it uses bulky bricks and heavy tires. It also uses different tire sizes in the front and back causing an imbalance. Do not include any sensors. Target placement is very important. So be careful!

4. Example Cars Built by Participants

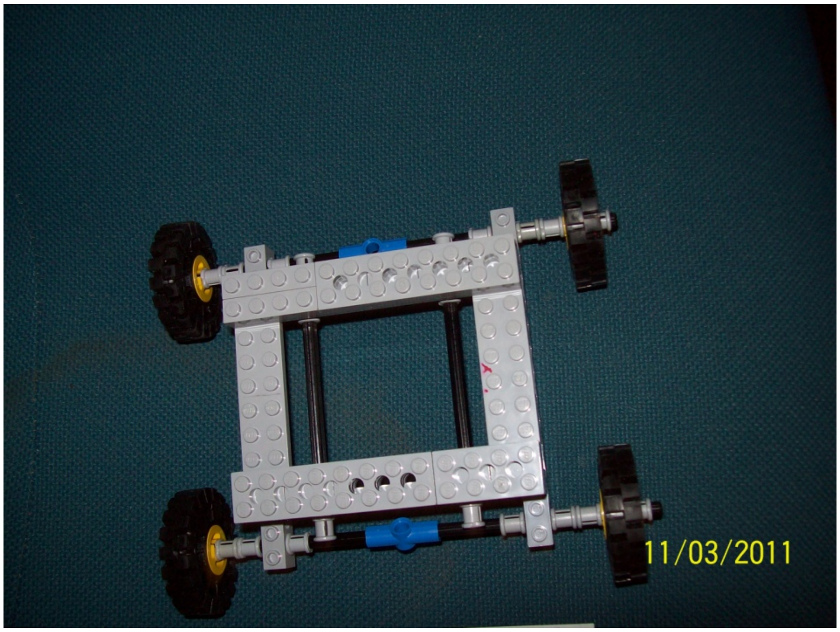



16
15
Team: 1 Car: 2 Design: 1

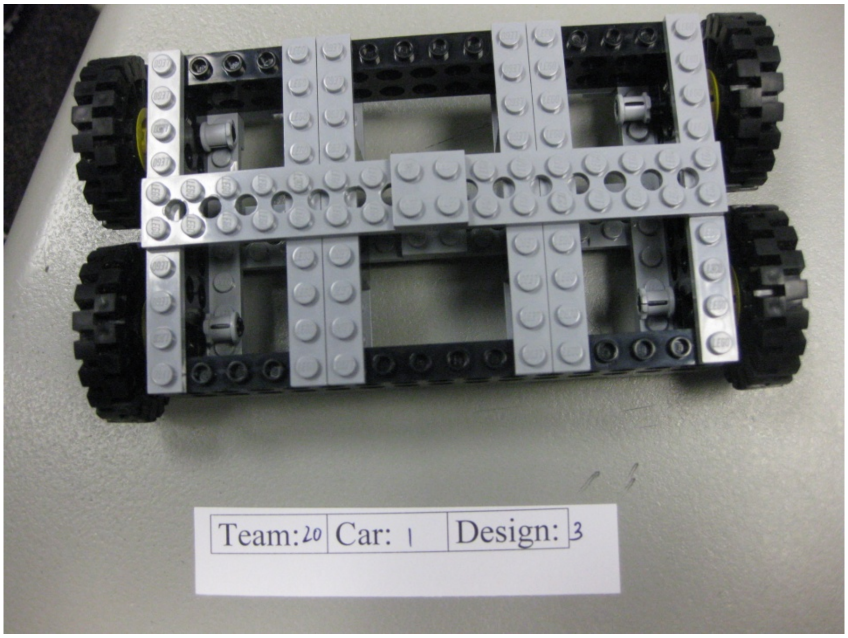

Team: 15 Car: 1 Design: 1


Team:3
Car: A
Design: 2


Team:10
Car: A
Design:3

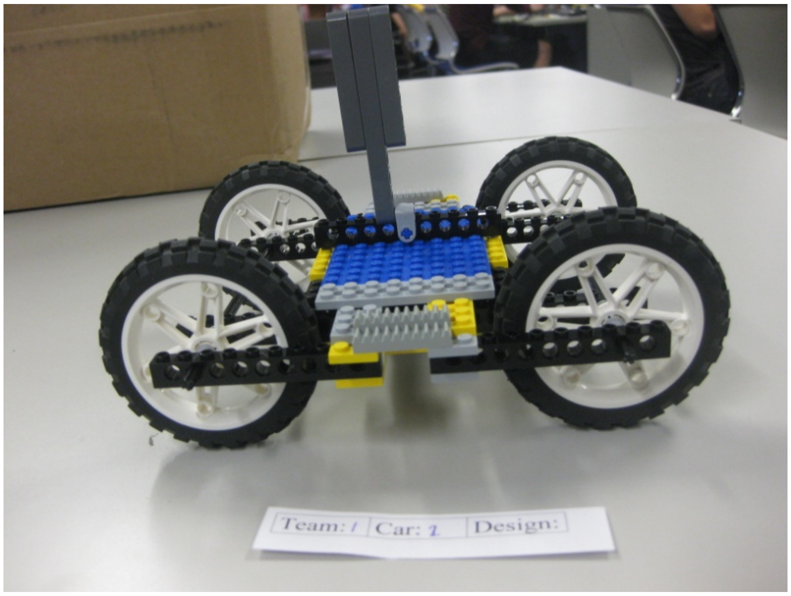


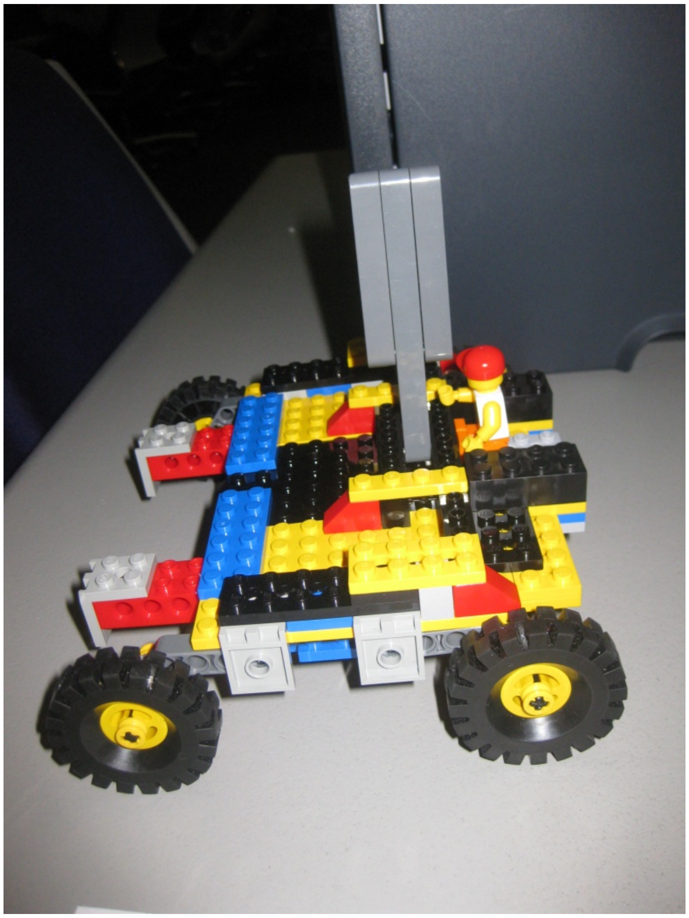
11/03/2011



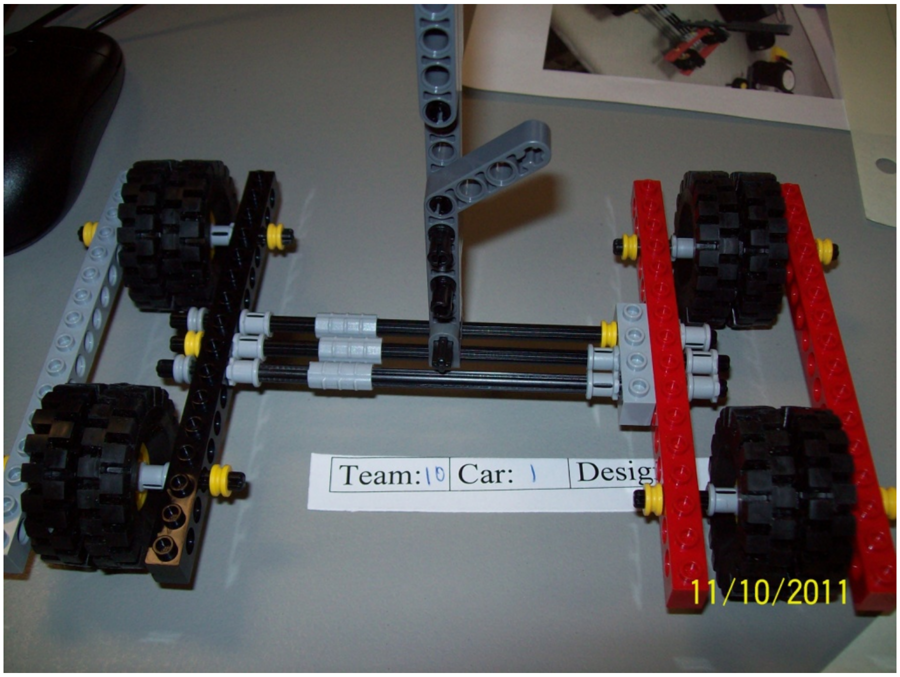
Team: 20 Car: 1 Design: 3

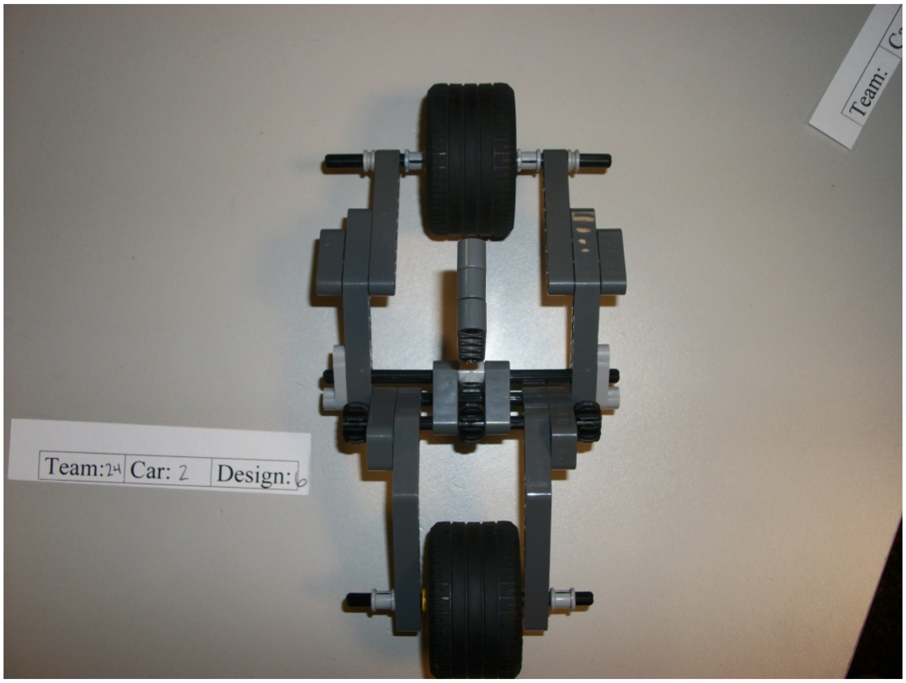

11/03/2011
4:02
Design: 1


Team: 1
Car: 2
Design:




Team: 11
Car: 1
Design:
11/10/2011


Team: 10 Car: 1 Desig
11/10/2011


Team: 24 Car: 2 Design: 6
Team: C

APPENDIX E

MATERIALS USED FOR THE DEVELOPMENT AND TESTING OF MODEL ERROR REDUCTION METHOD

1. Experiment Script Used for Testing MERM

Consent

PEN: BLACK
ON TABLE: CONSENT FORMS (2 COPIES), PROBLEM STATEMENT, BLANK SHEETS OF PAPER.

When participants come, show them the work place.

“**Hello and thank you for taking time to participate in this research study today. We are beginning with the experiment. Please turn off all cell phones.”**

“You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

In this study, you will be asked to complete a design task. The study will require approximately 3 hours. Please let me know if you have any questions about the experiment.”

Wait until all of the participants have finished reading to proceed with the experiment. Then say**, “If you agree to participate please sign the form and keep the second copy for your records.”**

Wait for participants to sign the consent forms

Collect the consent forms.

“**This experiment has multiple activities and all three hours will be required. Your effort will be compensated with extra credits for your design class/monetary compensation. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after January 1, 2013 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?”**

Answer the questions if any.

Initial Design Activity

"Let us start with the experiment. This experiment aims to improve the design procedure followed currently. In this study, you will develop a detailed design for a mechanical system that you are familiar with. There are three sections in this experiment. You will have 5 minutes breaks at every one hour. Please use the given pens and papers during the experiment. Your pen will be exchanged as needed. Raise your hand if you have any questions during the experiment."

"Please take the sheet of paper on the upper left corner of your table and turn it over. This sheet gives you the design problem and instructions to solve. Please read the problem and let me know if you have any questions."

Answer questions if any.

"You will get 90 minutes to complete this design. Try to complete as much as possible within the given time. You may number the parts in the figure of design problem statement and use these numbers to annotate parts in your design. I will give you a warning when only 5 minutes are left. Please draw necessary diagrams, add descriptions and list the formulae to be used as required. You can use as many sheets as you want. Number your sheets in the order you use them. Please list your steps very clearly. For your reference, "Shigley's Mechanical Engineering Design" textbook is available on your table. Are there any questions?"

"You may start now."

after 50 minutes **"You may take a 5 min break now. The restrooms are in this side of the room** (point in that direction) **and there is a water fountain around the corner."**

after 5 minutes **"Welcome back. You may continue with your design activity"**

*** After 35 minutes *** **"you have 5 minutes left"**

after 5 more minutes **"Please stop the activity now."**

Design with Chart 1

PEN: RED
ON TABLE: 15 COPIES OF TEMPLATE 1

"Please take the stack of paper on the upper left corner of your table, turn them over. Fill these templates for each part that you considered for your design. You may number the parts in the figure in the design problem statement and use those numbers in your templates. You need to draw the free body diagram of each part and list the forces in the table below. Also indicate whether you considered these forces in your design. If not and if you think that force is important for your design, you may go back and make the necessary changes in the design. You can also make any other necessary changes in your design if you wish to. If you could not complete the design in the previous activity, you need to fill the templates only for the parts that you finished designing. Use one sheet per part. You will get 30 minutes to complete this activity. I will give you a 5 minute warning. Are there any questions?"

*** after 30 minutes*** **"You have 5 minutes left to complete this activity"**

*** after 35 minutes*** **"Please stop this activity. You may take another 5 minutes break now."**

Design with Chart 2

PEN: BLUE
ON TABLE: 15 COPIES OF TEMPLATE 2

"Please take the stack of paper on the upper left corner of your table, turn them over. Fill these templates for each connection in the design. Fill one sheet per pairs of parts in contact. You need to draw the free body diagram of the connection and list the forces in the table below. Also indicate whether you considered these forces in your design. If not and if you think that force is important for your design, you may go back and make the necessary changes in the design. You can also make any other necessary changes in your design if you wish to. Use one sheet per connection. You will get 30 minutes to complete this activity. I will give you a 5 minute warning. Are there any questions?"

*** after 30 minutes*** **"You have 5 minutes left to complete this activity"**

*** after 35 minutes*** **"Please stop this activity."**

Closure

"This concludes your portion in this study. Thank you for your participation. Please leave all your papers on the table itself. What do you like for your compensation? You can either take extra credit in your design class or money ($35). Remember that if you accept money, you WILL NOT be eligible for extra credit in your class as offered."

Pay them/note information for extra credit.

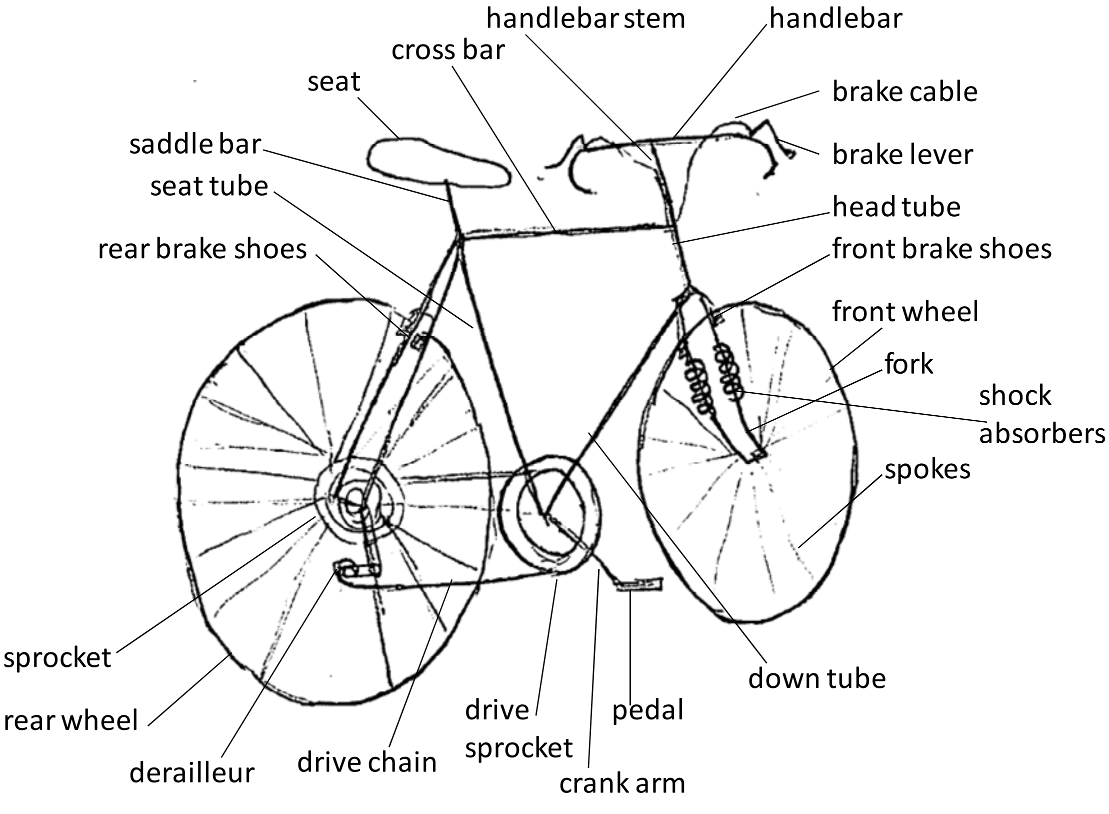
"Once again, thank you for your participation. Please remember not to discuss this study with your classmates or friends until after Jan 1, 2013 as it may bias the results. You may ask any questions you have about this study."

2. Design Problem Used for Testing MERM

Design Problem:

Your task is to design a bicycle and its components. Assume that the figure shown below is the concept generated by you. Your job is to develop a detailed design from this concept. You can make any assumptions as needed. Treat each member of the frame as a separate part. You need not design seat, tires and spokes.

List the procedure you follow to complete this design, including any formulae that you use. Include as much details as possible. Make sure to list any assumptions that you make for this design.



3. Template 1 in MERM (for missing loads)

Part name/number:

Free body diagram: (You may annotate your forces and use these annotations in the table below)

List the forces that you drew on the free body diagram in the following table:

Force acting on the part	Type of force (tension, compression, bending, shear etc.)	I considered this force in my original design (Y/N)

4. Template 2 in MERM (for missing connection designs)

Part name/number:

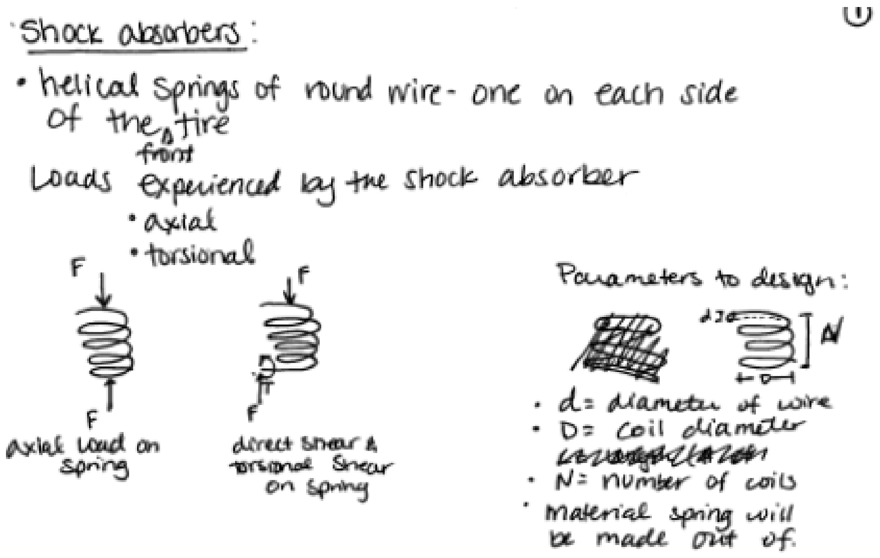
Part name/number:

Free body diagram: (of the two parts showing the forces between them - You may annotate your forces and use these annotations in the table below)

List the forces that you drew on the free body diagram in the following table:

Force acting on interface	Type of force (tension, compression, bending, shear etc.)	Part on which the force acts	I considered this force in my original design (Y/N)

5. <u>Sample Raw Data from the Experiment (1 Participant)</u>



①

Shock absorbers:

- helical springs of round wire - one on each side of the front tire

Loads experienced by the shock absorber
- axial
- torsional

F

F

axial load on spring

F

F

direct shear & torsional shear on spring

Parameters to design:

d

D

N

- d = diameter of wire
- D = coil diameter
- N = number of coils
- material spring will be made out of.

Pedal

②

- lightweight — corrosion resistant (don't want pedals corroding if bike is left outside)
- hold its shape (not deform under loads)
- easy to replace

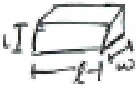
- ~~Assume the pedal only experiences axial loads.~~

F_R = force applied by rider

$\boxed{\frac{F_R}{A} = \text{stress}}$

- force experienced by the pedal will not be constant - it will cyclically change

Parameters to design:

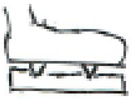


l = length
h = height
w = width

- material pedal will be made from

material possibly a composite?
- fibers provide stiffness and strength
- matrix holds material together & transfers the load.

- Assuming this bike is a higher-quality street bike and not a bike for a young child
    - The pedals must incorporate a "grip" to hold the rider's shoes in place.
    - This grip must hold the shoes in place, but not be too hard for the rider to remove his ~~[illegible]~~ foot if he needs to and avoid injury.



- Shoe has spikes to hold it in place,
- pedals have [illegible] channels for the spikes to slide into place. The rider slides foot forward to lock them in place, and backwards to release his foot.

③

Brake Lever

- lightweight
  - easy to operate
  - fits geometry of human hand

Parameters to design:

- material selection
- slope of handle
- w = width of lever
- l = length of lever (not accounting for curved ends)
- t = thickness of lever

Loading:

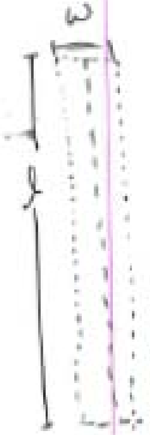
= axial load applied by the rider's hand.

$\sigma = \frac{F}{A}$ where A is the area of the "straight part"

T = torsional force from rider's hand.

$l \approx 3\text{-}4$ in

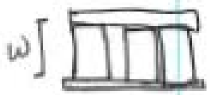
$w \approx .5$in-1in



Drive Chain and Drive Sprocket

④

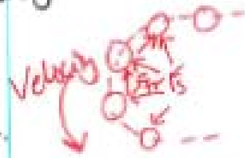
Chain Parameters to design:



- w: width, space b/t the inner link plates

- P= pitch, linear distance between the centers of the rollers
- [illegible] type of strand → Single
- Roller Diameter

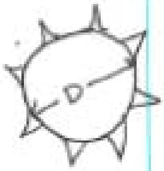
γ= pitch angle



F_s = force from sproket
F_{fr} = frictional force

Sproket

- D = Pitch diameter of the sproket
  - N = # of sproket teeth



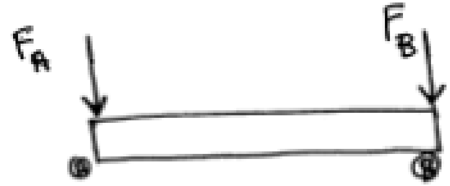
– Design N so operation is smooth, chain "noise" is minimized, and life expectancy is optimized.

$$\left.\begin{aligned} D &= \frac{P}{\sin(\gamma/2)} \\ \gamma &= 360^\circ/N \end{aligned}\right\} D = \frac{P}{\sin(180^\circ/N)}$$

- The primary failure concern for the drive chain and drive sprocket is [illegible] wear of the rollers or pins.

Cross Bar

⑤



Assume cross bar only experiences axial loads
(In reality, the bar most likely experiences some torsional
load, esp. @ location B when the bike is steered)

- Bar is circular cross section

max shear stress due to bending: $\tau_{max} = \frac{4V}{3A}$

F_A & F_B create a bending moment

$\sigma_{max} = \frac{Mc}{I}$

Parameters to design:

l = length of bar

D = diameter of bar

material selection - corrosion resistant, stiff material

Part name/number: Shock Absorbers

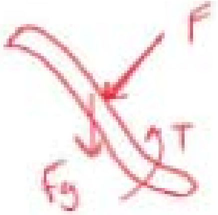
Free body diagram: (You may annotate your forces and use these annotations in the table below)

List the forces that you drew on the free body diagram in the following table:

Force acting on the part	Type of force (tension, compression, bending, shear etc.)	I considered this force in my original design (Y/N)
Fc	compressive	Y
Fs	Shear	Y
T	torsional shear	Y
Fg	gravity	N

Part name/number: Break lever

Free body diagram: (You may annotate your forces and use these annotations in the table below)



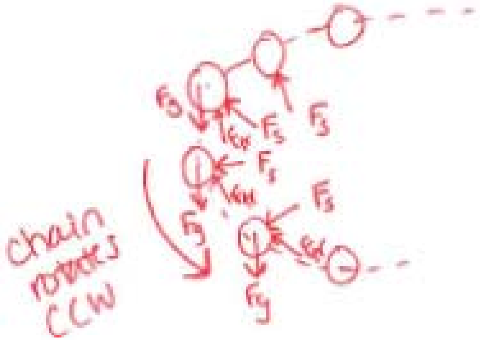
Rider's hand will
most like induce a
torsional force

List the forces that you drew on the free body diagram in the following table:

Force acting on the part	Type of force (tension, compression, bending, shear etc.)	I considered this force in my original design (Y/N)
F	compression	Y
T	torsion	N
Fg	gravity	N

Part name/number: Drive Chain

Free body diagram: (You may annotate your forces and use these annotations in the table below)

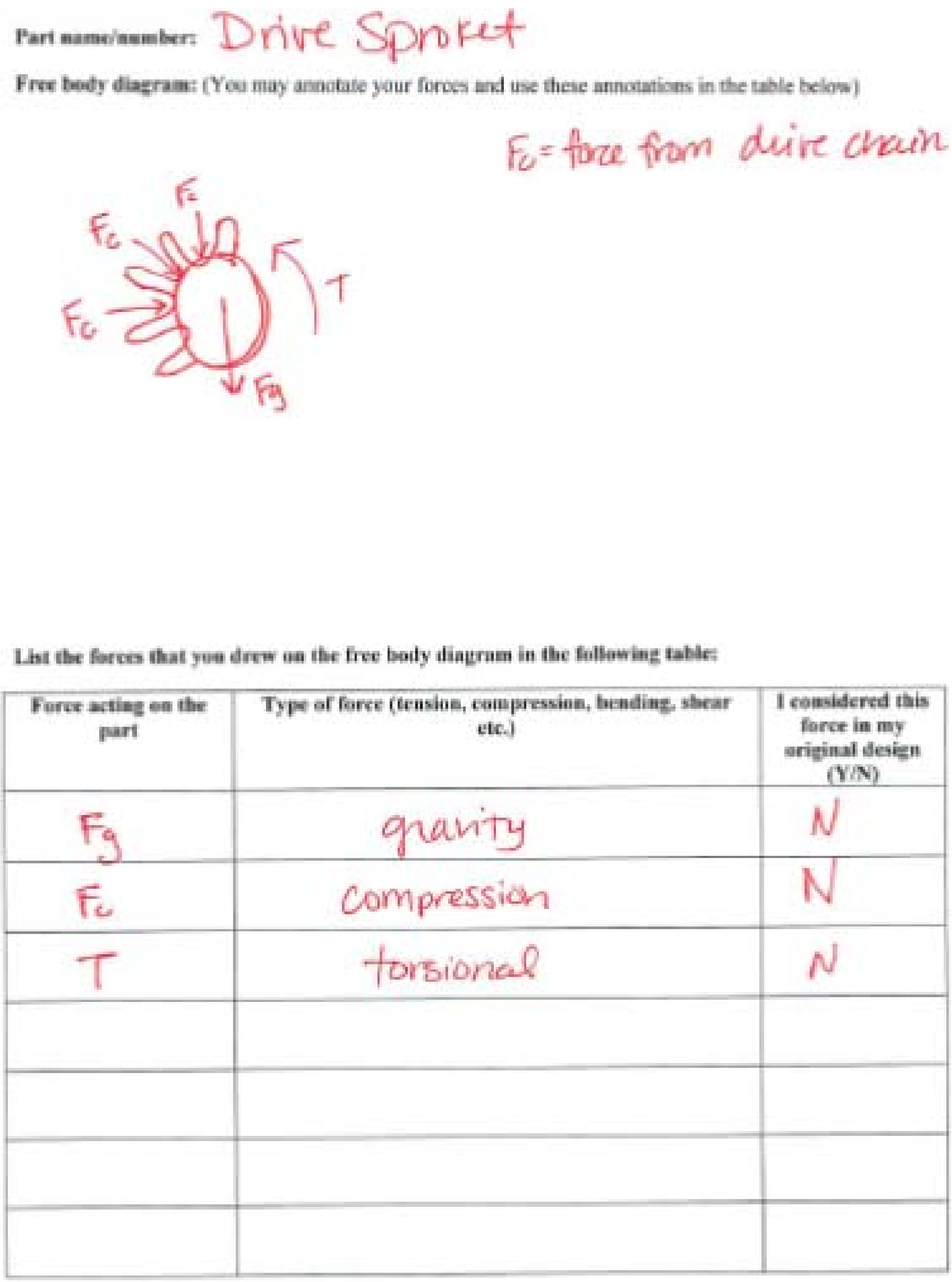


F_s = force from sproket

F_{fr} = force of friction
opposing motion of
chain acting
at contact point

List the forces that you drew on the free body diagram in the following table:

Force acting on the part	**Type of force (tension, compression, bending, shear etc.)**	**I considered this force in my original design (Y/N)**
F_s	compression	N
F_{fr}	friction	N
F_g	gravity	N



Part name/number: Drive Sproket

Free body diagram: (You may annotate your forces and use these annotations in the table below)

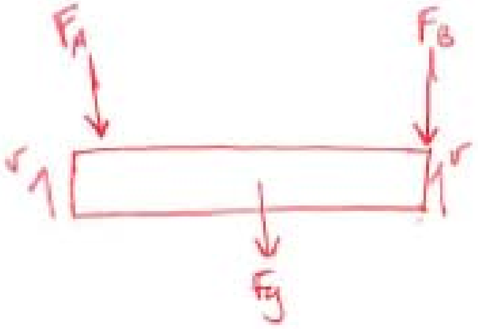
Fc = force from drive chain

List the forces that you drew on the free body diagram in the following table:

Force acting on the part	Type of force (tension, compression, bending, shear etc.)	I considered this force in my original design (Y/N)
Fg	gravity	N
Fc	compression	N
T	torsional	N

Part name/number: Cross Bar

Free body diagram: (You may annotate your forces and use these annotations in the table below)

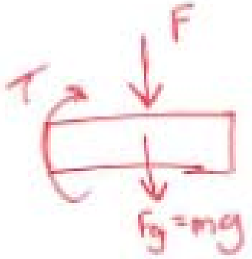


List the forces that you drew on the free body diagram in the following table:

Force acting on the part	Type of force (tension, compression, bending, shear etc.)	I considered this force in my original design (Y/N)
F_A	~~compression~~ bending	Y
F_B	~~compression~~ bending	Y
F_g	gravity	N
v	Shear	N

Part name/number: Pedal

Free body diagram: (You may annotate your forces and use these annotations in the table below)



T is the torsional force applied by the rider's foot

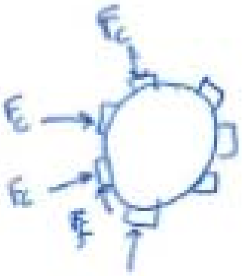
List the forces that you drew on the free body diagram in the following table:

Force acting on the part	Type of force (tension, compression, bending, shear etc.)	I considered this force in my original design (Y/N)
F	compression	Y
Fg	gravity	N
T	torsional	N

Part name/number: drive chain

Part name/number: drive sprocket

Free body diagram: (of the two parts showing the forces between them - You may annotate your forces and use these annotations in the table below)



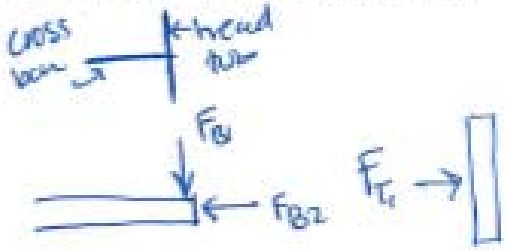
List the forces that you drew on the free body diagram in the following table:

Force acting on interface	Type of force (tension, compression, bending, shear etc.)	Part on which the force acts	I considered this force in my original design (Y/N)
F_{f1}	friction	drive and chain sprocket	N
F_3	compression	drive chain	N
F_c	compression	drive sprocket	N

Part name/number: cross bar

Part name/number: head tube

Free body diagram: (of the two parts showing the forces between them - You may annotate your forces and use these annotations in the table below)



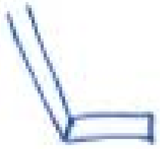
List the forces that you drew on the free body diagram in the following table:

Force acting on interface	Type of force (tension, compression, bending, shear etc.)	Part on which the force acts	I considered this force in my original design (Y/N)
~~F_{B1}~~ F_{B2}	compression	cross bar	N
~~F_{B2}~~ F_{B1}	Bending	cross bar	N
F_{T_1}	compression	Head tube	N

Part name/number: Pedal

Part name/number: Crank aim.

Free body diagram: (of the two parts showing the forces between them - You may annotate your forces and use these annotations in the table below)



List the forces that you drew on the free body diagram in the following table:

Force acting on interface	Type of force (tension, compression, bending, shear etc.)	Part on which the force acts	I considered this force in my original design (Y/N)
F_C	compression	crank aim	N
F_{P_1}	compression	pedal	N
F_{P_2}	Bending	pedal	N
v	Shear	Both	N

Part name/number: Handle Bar

Part name/number: Handlebar Stem

Free body diagram: (of the two parts showing the forces between them - You may annotate your forces and use these annotations in the table below)

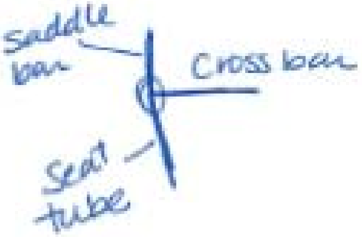
List the forces that you drew on the free body diagram in the following table:

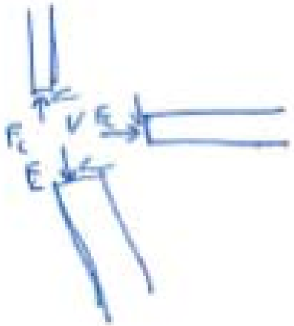
Force acting on interface	Type of force (tension, compression, bending, shear etc.)	Part on which the force acts	I considered this force in my original design (Y/N)
F_c	compression (contact)	Handlebar and stem	N
v	Shear	Both	N

Part name/number: Saddle bar + cross bar

Part name/number: Seat tube

Free body diagram: (of the two parts showing the forces between them - You may annotate your forces and use these annotations in the table below)





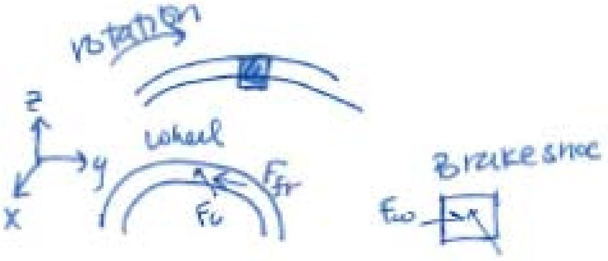
List the forces that you drew on the free body diagram in the following table:

Force acting on interface	Type of force (tension, compression, bending, shear etc.)	Part on which the force acts	I considered this force in my original design (Y/N)
F_c	compression (contact force)	All 3 parts	N
V	Shear	all 3	N

Part name/number: Rear Brake Shoes

Part name/number: Rear [illegible] wheel

Free body diagram: (of the two parts showing the forces between them - You may annotate your forces and use these annotations in the table below)



F_{fr} = frictional force applied when breaks are used

- (also, due to friction when breaking, there will be a temperature increase (at the interface). Although this does not affect the FBD, it should be accounted for in the design.)

F_w is force of wheel acting on break shoe from rotating.

List the forces that you drew on the free body diagram in the following table:

Force acting on interface	Type of force (tension, compression, bending, shear etc.)	Part on which the force acts	I considered this force in my original design (Y/N)
F_c	compression (contact)	Both	N
F_{fr}	friction	wheel	N
F_w	torsional	Break shoe	N

6. <u>Templates of MERM used for Graduate Design Course (Given as a home work)</u>

Part	**Type of Loading**[1]	**Associated Stress/Force Equation**	**Strength of the Material Used**	**Required Minimum Dimensions**	**Design Satisfactory (Y/N)**[2]
Note 1	Include a free body diagram of the part.				
Note 2	Does the design meet the required specifcations?				

Part 1	Part 2	Are They in Contact ? (Y/N)	If Yes, What Type of Contact	Contact Forces	Contact Force Critical to the Design?[1]	Value of Contact Force	Minimum Force Acting on Either Part[2]	Essential for Design? (Click Here for Metric)[3]
Note 1	If Yes, then this Contact Force is automatically essential to the design.							
Note 2	Can be taken from Chart 1.							
Note 3	If a contact force is >20% of the minimum force it may be considered important.							

7. Sample Index Cards Used for Content Analysis

Prototype is used to infer the effectiveness of airflow

R2F2010 - 1

Prototype is used to test Airflow speed at inlet vs. airflow at outlet

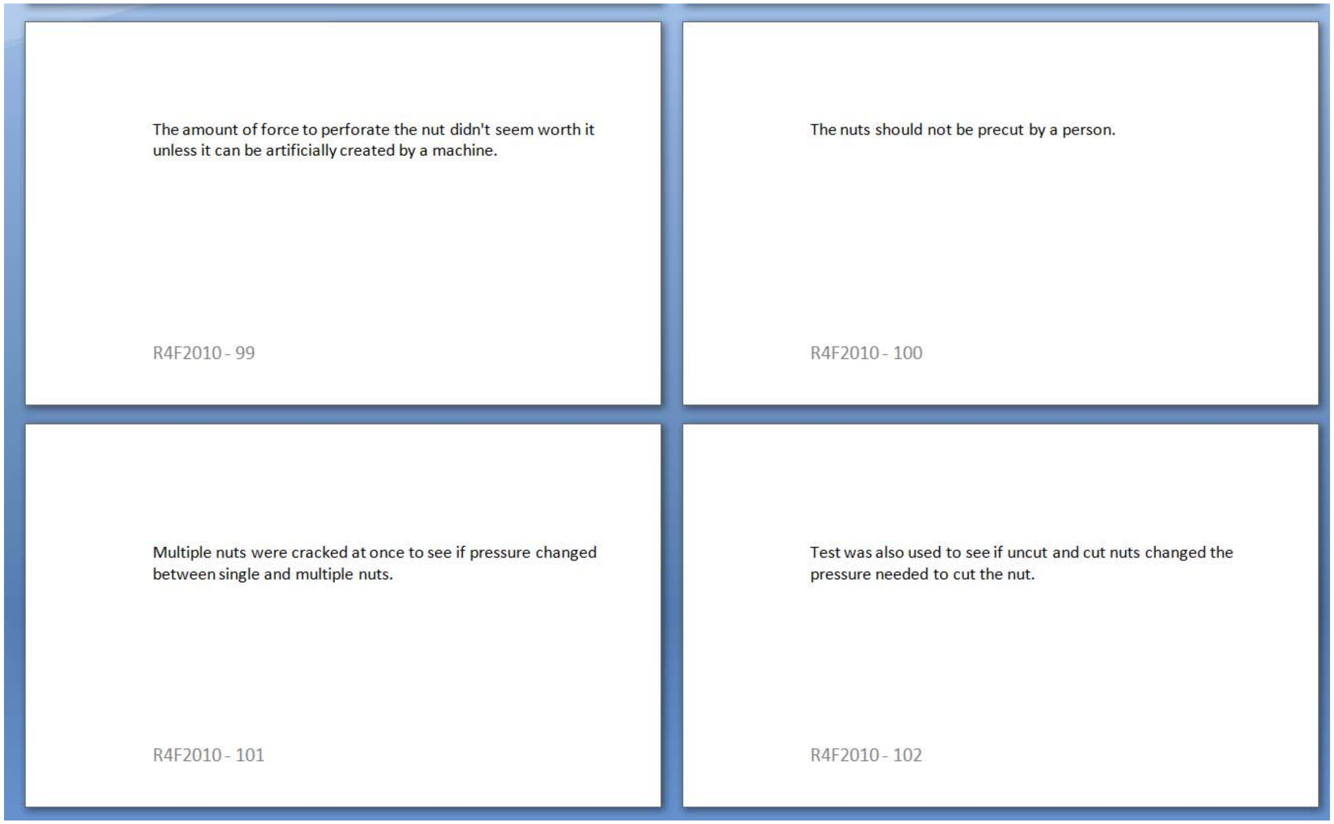
R2F2010 - 2

Prototype is used to test effectiveness of convective transfer

R2F2010 - 3

Prototype is used to test time it takes to put jacket on

R2F2010 - 4



The amount of force to perforate the nut didn't seem worth it unless it can be artificially created by a machine.

R4F2010 - 99

The nuts should not be precut by a person.

R4F2010 - 100

Multiple nuts were cracked at once to see if pressure changed between single and multiple nuts.

R4F2010 - 101

Test was also used to see if uncut and cut nuts changed the pressure needed to cut the nut.

R4F2010 - 102

Most of the principles are the same with the first one, we only changed the activated force from rotating force to a straight force.

R3F2010 - 75

We added slots in order to prevent the sections falling off since the gravity.

R3F2010 - 76

Without these slots, every time before we inserting our device into the drainage layer, we need to hold all sections together by our hands.

R3F2010 - 77

This slot should have enough space to let sections expand.

R3F2010 - 78

APPENDIX F

EXPERIMENT MATERIALS AND SAMPLE DATA FROM THE FIXATION EXPERIMENT

1. Experiment Script

Check List

1. Design problem and materials
2. Blank Sheets
3. Script & Time sheet
4. Different color pens
5. Consent forms

1. Consent

When participants come, show them the work place.

Start stop watch.

"Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. So, please keep your watches and cell phones in your back pack or the box on this table "(Show the box). **"Also please don't use your pens to sketch."**

Check to make sure that the participants have no mobiles or watches with them.

"You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

You will be asked to generate ideas to solve multiple design problems. The study will require approximately 3 hours. Please let me know if you have any questions about the experiment."

Wait until all of the participants have finished reading to proceed with the experiment. Then say**, "If you agree to participate please sign the form and keep the second copy for your records."**

Wait for participants to sign the consent forms

Collect the consent forms.

"Please put away your copy of the consent forms."

This experiment has multiple activities and all three hours will be required. Your effort will be compensated with extra credits for your design class. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after September 1, 2011 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

Record the questions and answers in case of any.

Answer the questions if any.

2. *Design problem 1*

This experiment is seeking to understand the engineering idea generation. Today your task will be to generate as many ideas as possible that could help to solve the given design problem. This experiment has two sections. In each section you will solve a design problem. You will have 5 minute breaks at every one hour. Your pen will be exchanged to keep track of when the ideas are generated. The goal is to generate as many solutions as possible to the given design problem.

Please take the sheets of paper on the upper left corner of your table. The first sheet gives you the instructions to solve the problem and the remaining sheets give you the details of the design problem. You have 5 minutes to read the problem. I will give you instructions to begin at the end of five minutes.

Your five minutes starts now.

at the end of 5 min **Do you have any questions?**

Record if any.

You may start now.

at the end of 1 hour **Please stop the idea generation now.**

You may take a 5 min break now. The restrooms are outside this room on the other side and there is a water fountain around the corner. Please be back on time.

3. *Design problem 2*

Welcome back. Let us start your second task of the day. Please take the sheets of paper on the upper left corner of the table, turn them over. You will find your new design problem. Please generate as many solutions as possible to solve this design problem. Please read the problem. If you have any questions, please let me know

at the end of 2 hours **you may take another 5 min break now.**

at 2 hours and 50 min **Please stop the idea generation.**

Before you leave, I want one more piece of information from you. What is your major?

Thank you for your participation and I will make sure that you will receive your extra credit. This concludes your portion of the study. Please remember to not discuss this study with your classmates until after September 1, 2011 since this will bias the data. If you have any questions about this study I can answer them at this time. "

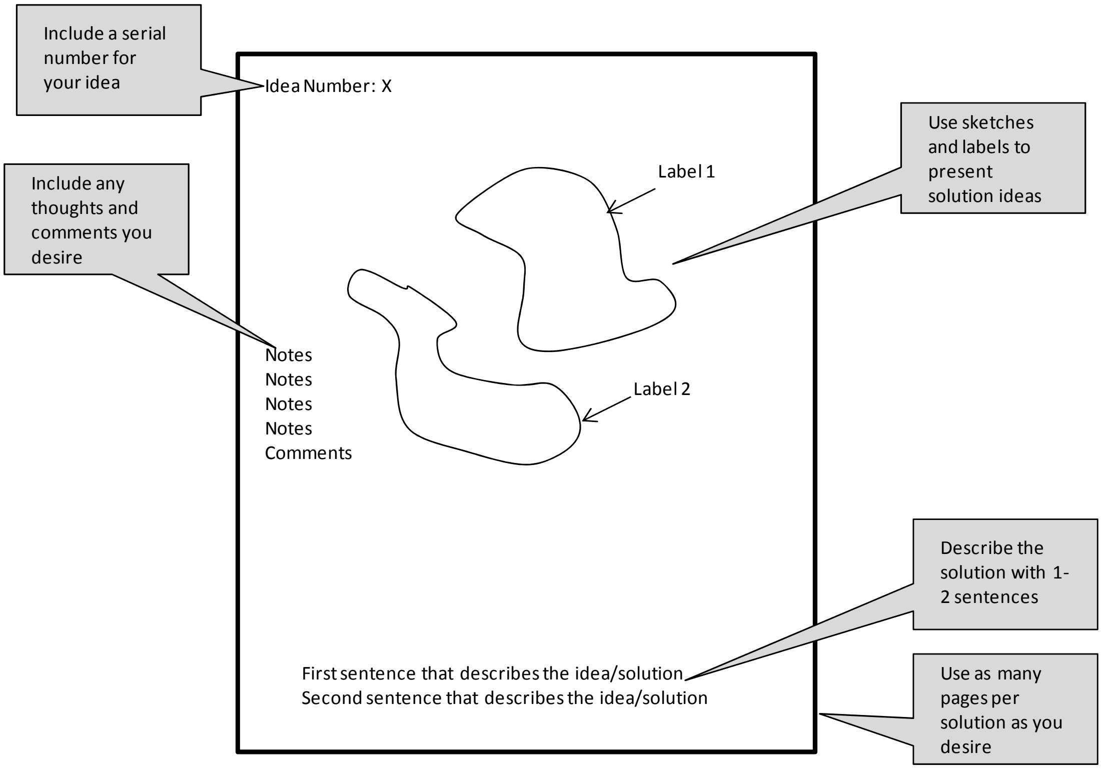
2. Design Problem & Instructions - Control Condition

Instructions

Consider the design problem on the following page. Please read these instructions and the design problem description carefully. You will be given up to 5 minutes to read this information, followed by 45 minutes to create design solutions to the design problem. Your goal is to create ***as many solutions to the problem as possible***.

Use provided sheets of paper to record your solutions. Each solution should be on a separate page. Your pen will be exchanged at regular intervals to keep track of when the ideas are generated.

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 as you develop each solution."



Include a serial number for your idea

Include any thoughts and comments you desire

Use sketches and labels to present solution ideas

Describe the solution with 1-2 sentences

Use as many pages per solution as you desire

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal 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.

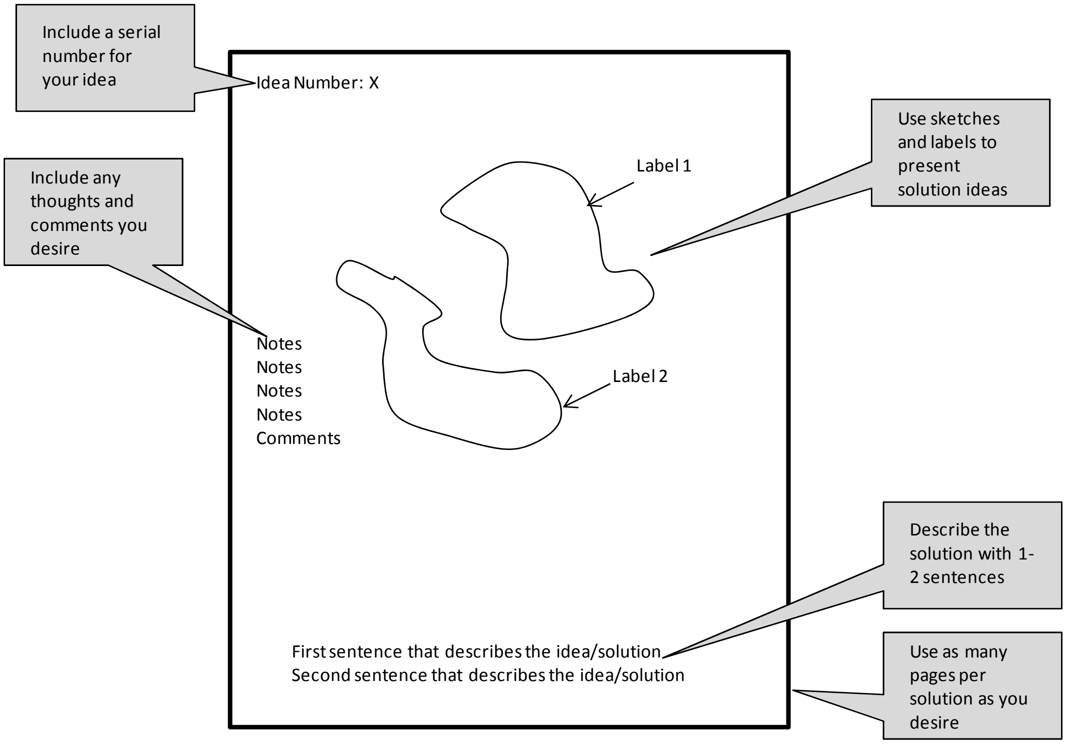
3. Design Problem & Instructions - Fixation Condition

Instructions

Consider the design problem on the following page. Please read these instructions and the design problem description carefully. You will be given up to 5 minutes to read this information, followed by 45 minutes to create design solutions to the design problem. Your goal is to create ***as many solutions to the problem as possible***.

Use provided sheets of paper to record your solutions. Each solution should be on a separate page. Your pen will be exchanged at regular intervals to keep track of when the ideas are generated.

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 as you develop each solution.”



Include a serial number for your idea

Include any thoughts and comments you desire

Use sketches and labels to present solution ideas

Describe the solution with 1-2 sentences

Use as many pages per solution as you desire

Design Problem - **Device to Shell Peanuts**

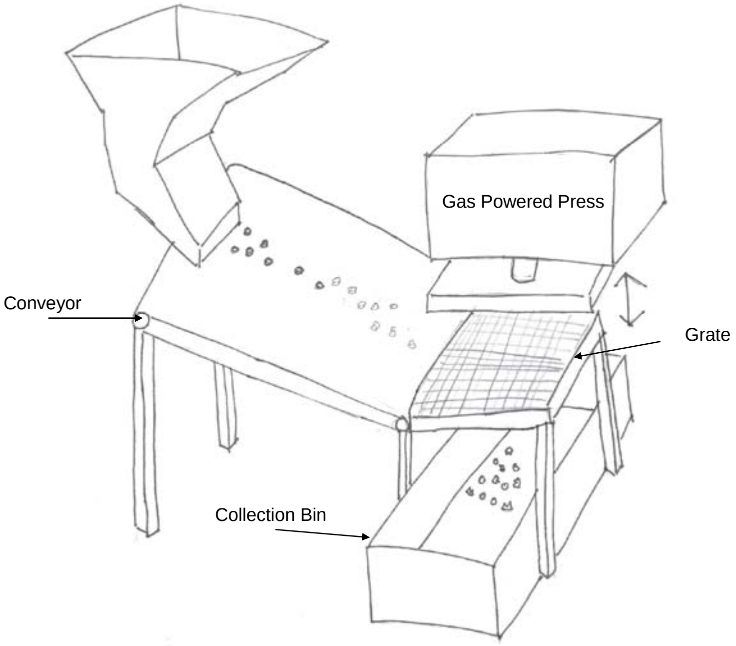
Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal 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.

Consider the following solution as an example that might be created for this design problem.



Solution Description: This system uses a gas powered press to crush the peanut shell. The shell and peanut then fall into a collection bin.

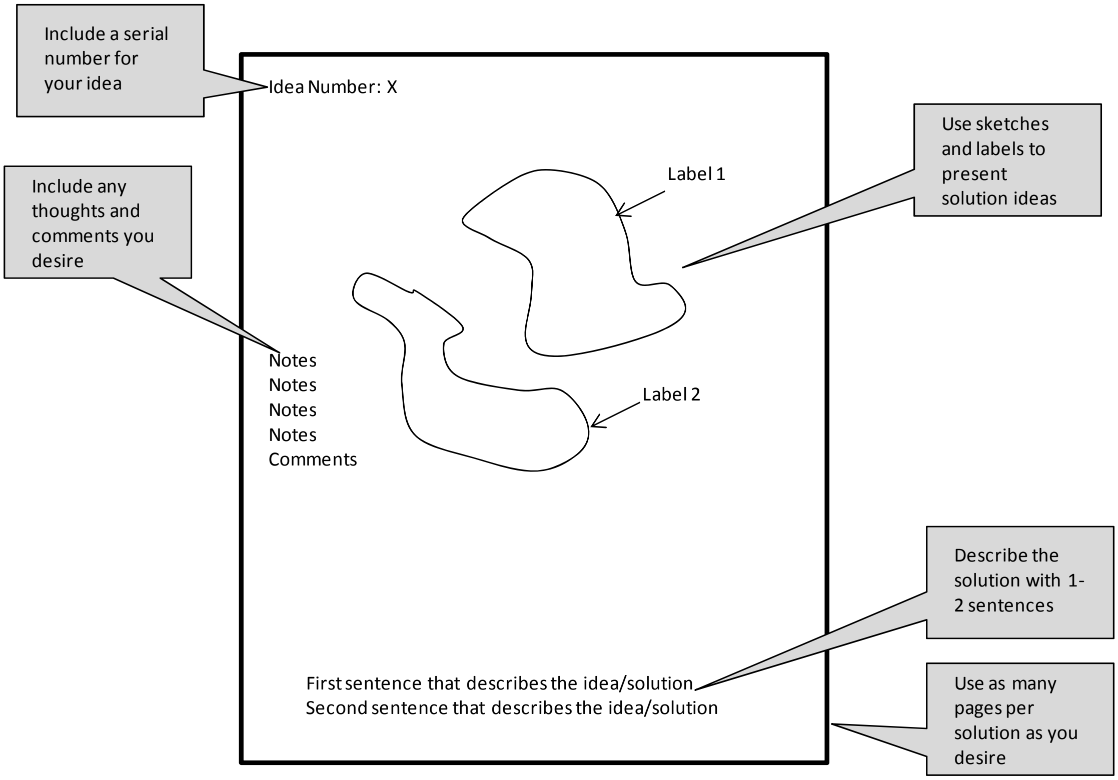
4. Design Problem & Instructions - Defixation Condition

Instructions

Consider the design problem on the following page. Please read these instructions and the design problem description carefully. You will be given up to 5 minutes to read this information, followed by 45 minutes to create design solutions to the design problem. Your goal is to create ***as many solutions to the problem as possible***.

Use provided sheets of paper to record your solutions. Each solution should be on a separate page. Your pen will be exchanged at regular intervals to keep track of when the ideas are generated.

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 as you develop each solution."



Include a serial number for your idea

Include any thoughts and comments you desire

Use sketches and labels to present solution ideas

Describe the solution with 1-2 sentences

Use as many pages per solution as you desire

Design Problem - Device to Shell Peanuts

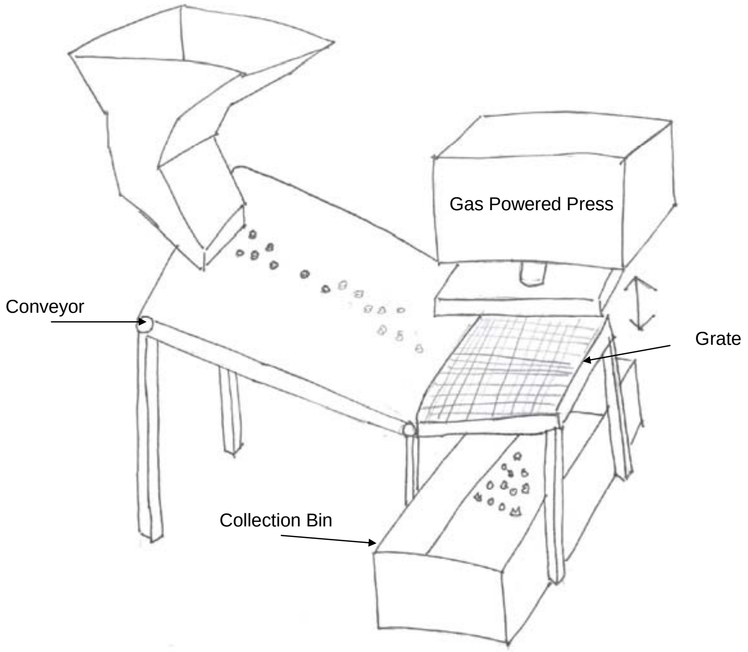
Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal 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.

Consider the following solution as an example that might be created for this design problem.



Solution Description: This system uses a gas powered press to crush the peanut shell. The shell and peanut then fall into a collection bin.

To assist you in developing as many designs as possible, consider the following clarification to the problem:

Functions:

- Import natural or human energy to the system
- Convert and transmit energy to peanut
- Remove peanut shell (remove outer structure from inner material)
- Separate removed shell (outer structure) from peanut (inner material)

Example Analogies that You Might Find Helpful:

- Hull
- Shuck
- Husk
- Clean (clean a deer, clean a fish or scale a fish)
- Soak
- Heat, Roast
- Dissolve
- Pod
- Pit, stone
- Burr (deburr something)
- Ream
- Bark (bark a tree)
- Skin
- Pare apples
- Pluck, deplume (strip feathers)
- Peel
- Grind (like a nut grinder)
- Brittle fracture

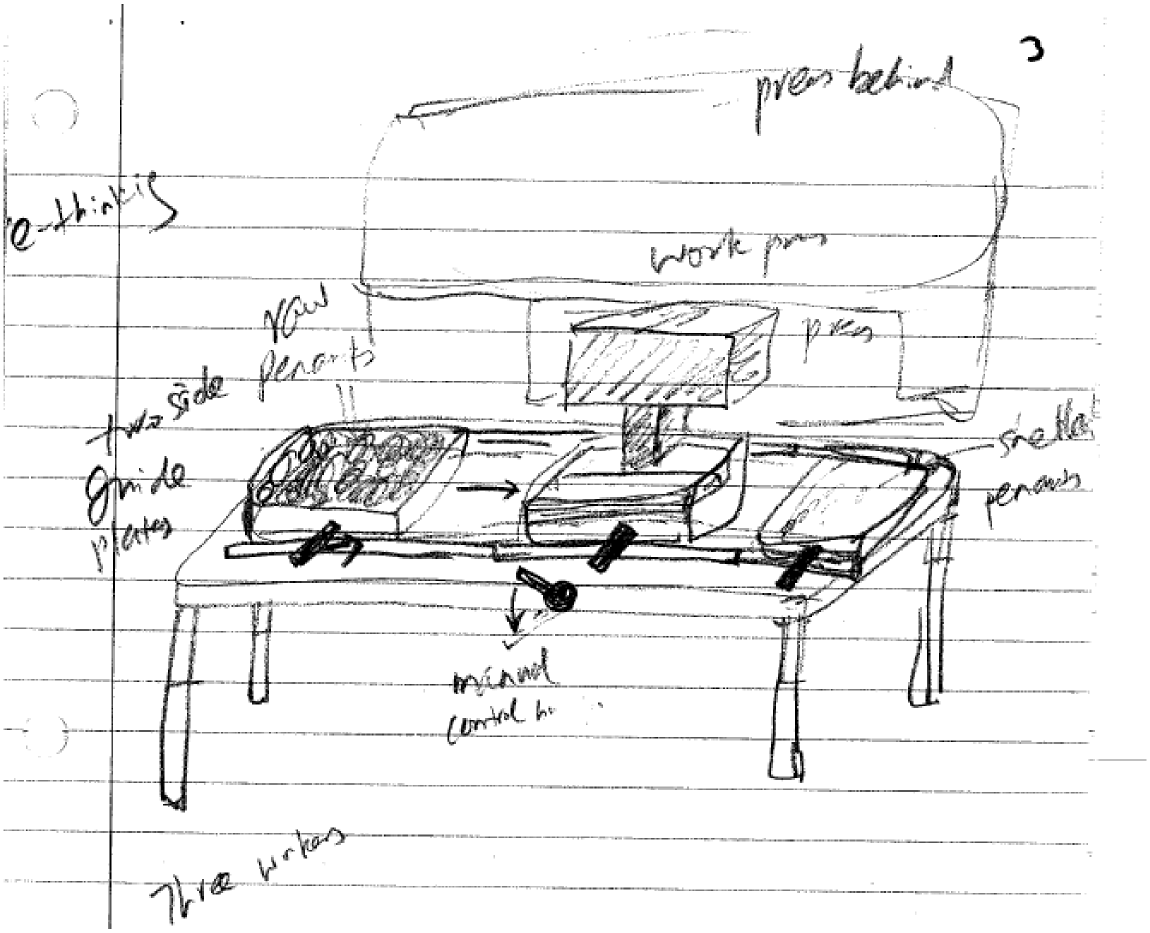
Natural Energy Sources Available:

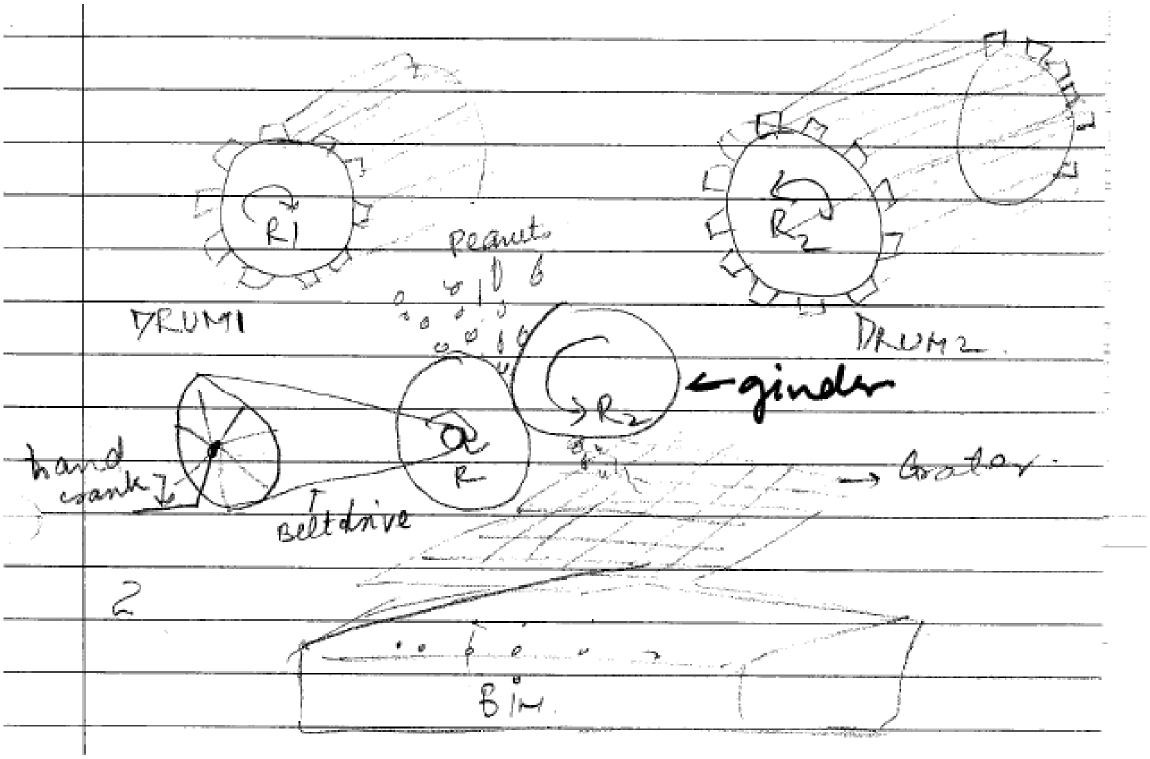
- Wind
- Solar
- Running water streams
- Captured rain water at a height
- Solar
- Human
- Animal

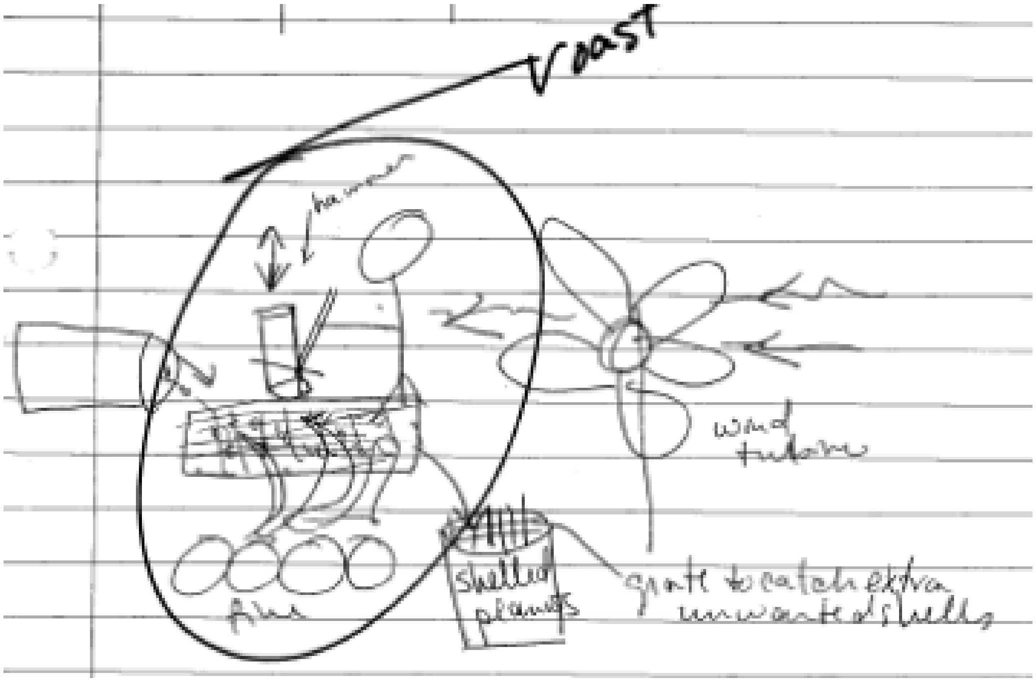
Back-of-the-envelope Calculations:

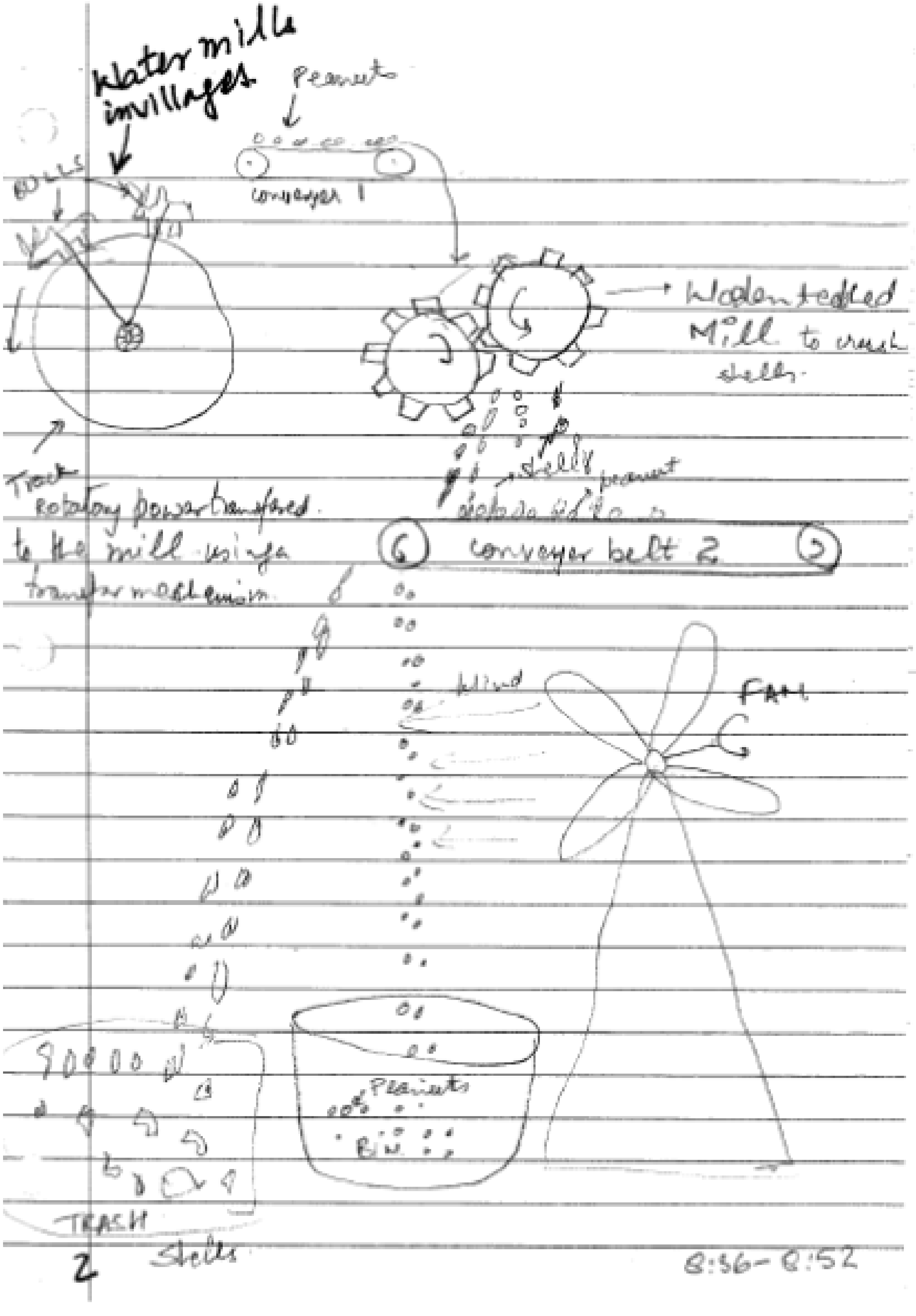
A quick analysis shows that a much greater quantity of power (or force) is needed to act on many peanuts simultaneously compared to applying power to a few peanuts at a time.

5. Example Concepts Generated by Design Faculty




R1
R2
peanuts
DRUM1
DRUM2
ginder
hand crank
Beltdrive
R
R2
Grater
2
Bin

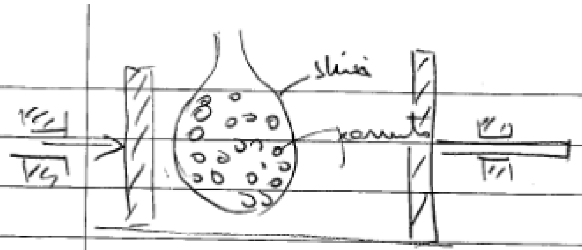

roast
hammer
wind turbine
shelled peanuts
grate to catch extra unwanted shells
Ash



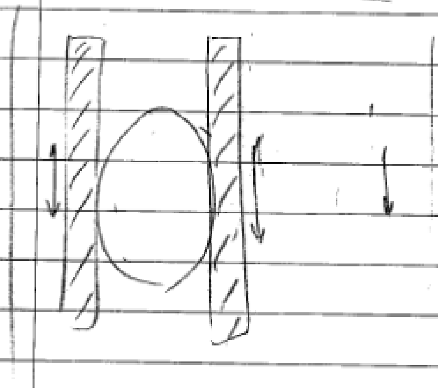
rotatory power transfered to the mill using a transfer mechanism.

2

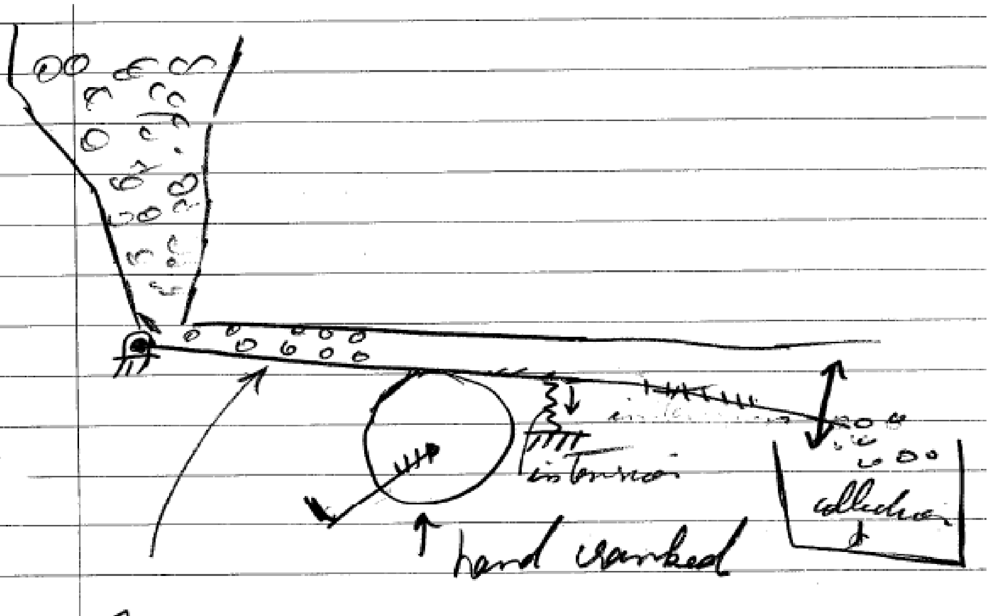
8:36-8:52



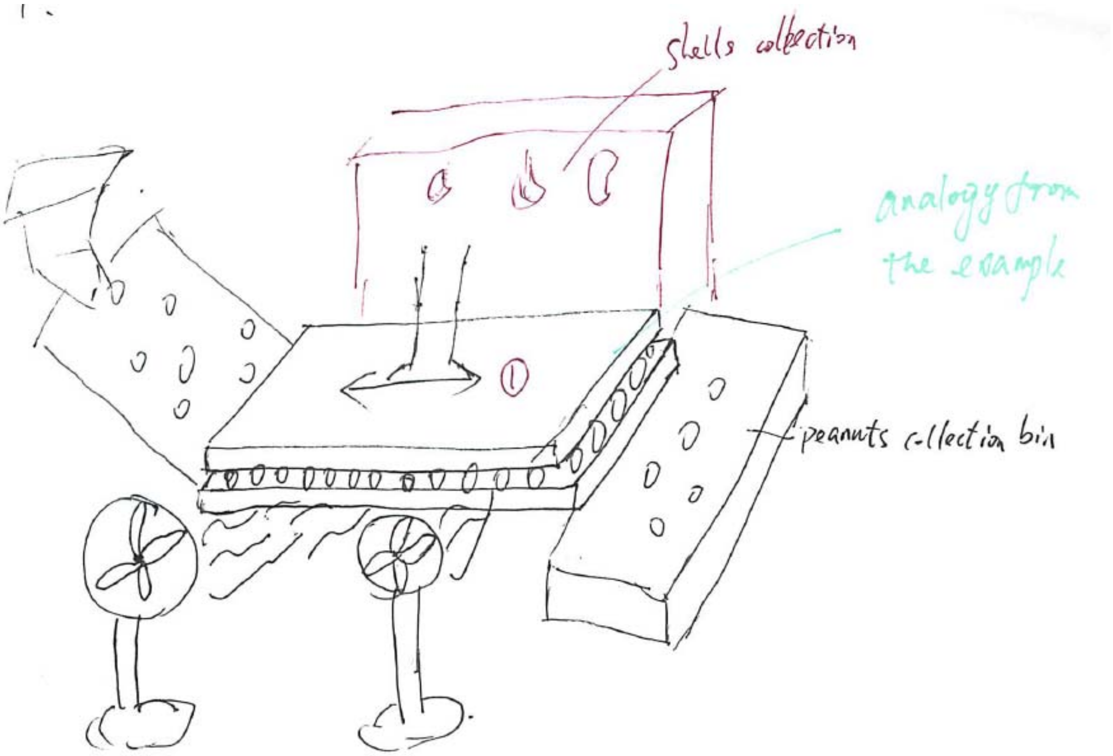
Step 1: the plates compress the skin and the peanuts with a relatively low force

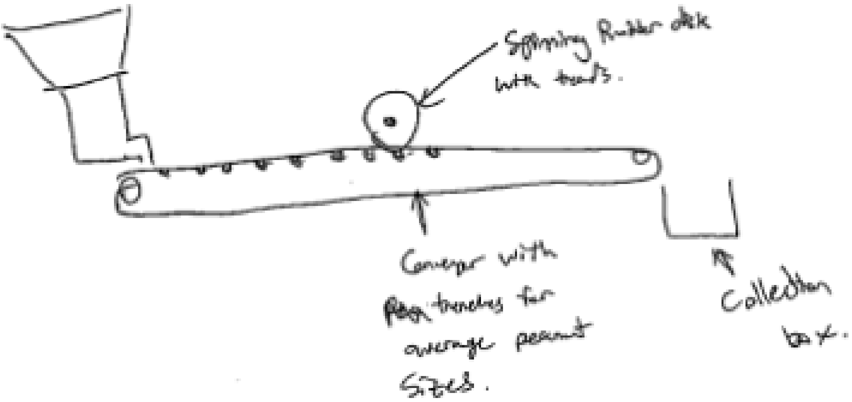


step 2. the plates start moving sideways while continuing to get closer to each other.

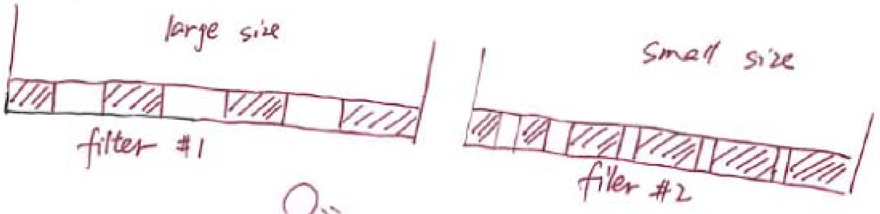


6. Example Concepts Generated by Students



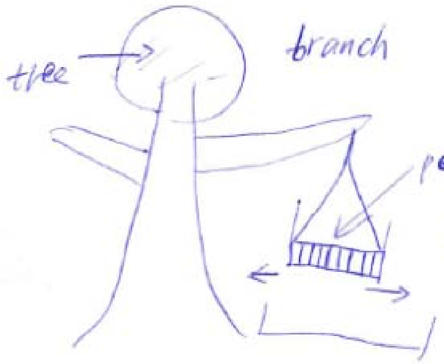


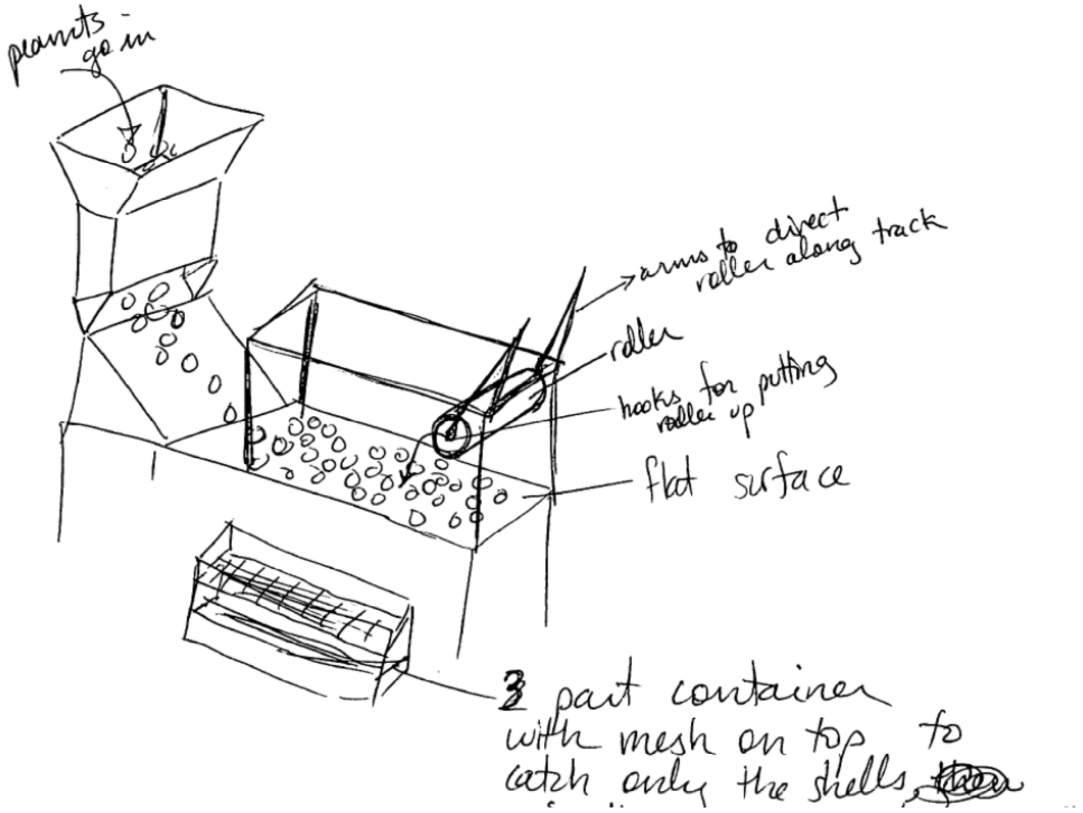
step 1. Sorting out different size of peanuts

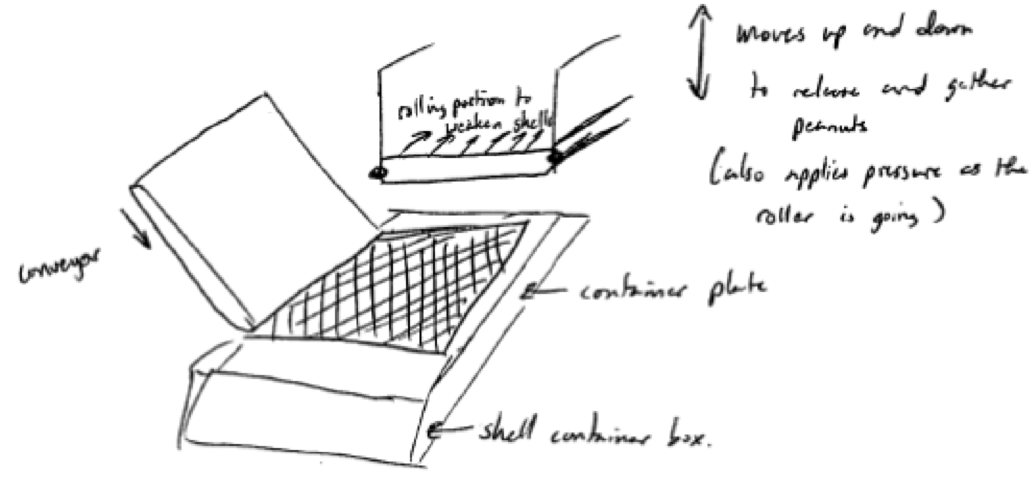


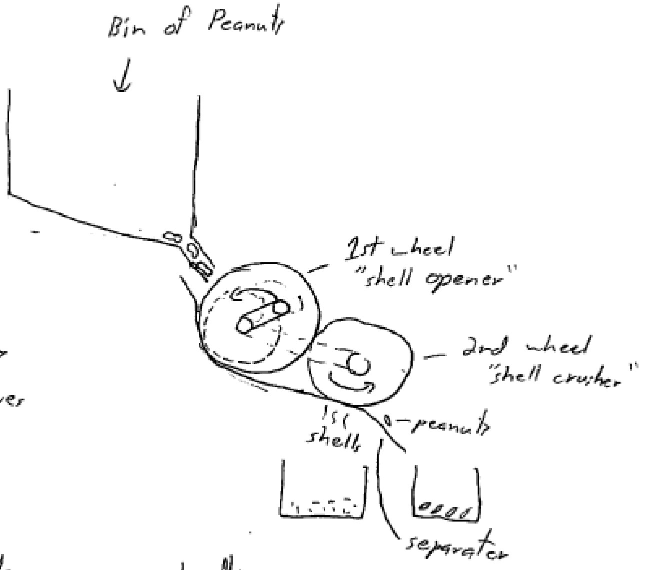
step 2

step 3 clean out the peanut shells




peanuts go in
arms to direct roller along track
roller
hooks for putting roller up
flat surface
3 part container with mesh on top to catch only the shells,

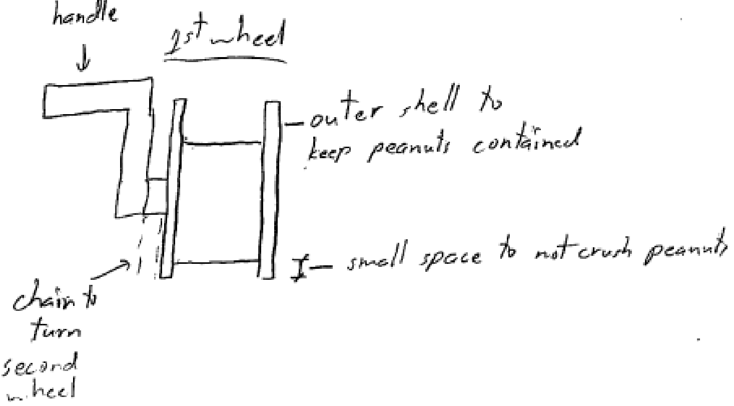

moves up and down to release and gather peanuts
(also applies pressure as the roller is going)
rolling portion to weaken shells
conveyor
container plate
shell container box.



1st wheel only opens shell. Leaves enough room for peanut to not be crushed

2nd wheel: made of softish material that won't crush peanut, but will crush shell into tiny pieces.

Separater; separates smaller shell pieces from whole peanuts.



This machine utilizes two wheels. One to break open shell, and the other to crush the shell into pieces while leaving the peanut undamaged.

Time: 11:45 am

APPENDIX G

EXPERIMENT MATERIALS AND SAMPLE DATA FROM THE FIXATION EXPERIMENT WITH PHYSICAL EXAMPLE

1. Experiment Script

Check List

1. Design problem and materials
2. Blank Sheets
3. Script & Time sheet
4. Different color pens
5. Consent forms

1. Consent

When participants come, show them the work place.

Start stop watch.

“Hello and thank you for taking time to participate in this research study today. Please turn off all cell phones. For this study, you are not supposed to monitor time using your watches or cell phones. Also please don’t use your pens to sketch.

Check to make sure that the participants have no mobiles or watches with them.

“You are being asked to participate in a research study on engineering design. Please read the consent form. You are not required to participate in this study and may end your participation at any time.

You will be asked to generate ideas to solve multiple design problems. The study will require approximately 3 hours. Please let me know if you have any questions about the experiment.”

Wait until all of the participants have finished reading to proceed with the experiment. Then say**, “If you agree to participate please sign the form and keep the second copy for your records.”**

Wait for participants to sign the consent forms

Collect the consent forms.

"Please put away your copy of the consent forms."

This experiment has multiple activities and all three hours will be required. Your effort will be compensated with $8 per hour and $1 bonus upon completion of the experiment. Participants with greatest number of solutions will be paid $10 extra as a prize. You must agree to not discuss any aspects of the study with other students in mechanical engineering of Texas A&M until after September 1, 2012 since this will bias the results. Your participation is voluntary. Are there any questions before we begin?

Record the questions and answers in case of any.

Answer the questions if any.

2. *Design problem 1*

This experiment is seeking to understand the engineering idea generation. Today your task will be to generate as many ideas as possible that could help to solve the given design problem. This experiment has three sections. In each section you will solve a design problem. You will have 5 minute breaks at every one hour. Your pen will be exchanged to keep track of when the ideas are generated. The goal is to generate as many solutions as possible to the given design problem.

Please take the sheets of paper on the upper left corner of your table. The first sheet gives you the instructions to solve the problem and the remaining sheets give you the details of the design problem. You have 5 minutes to read the problem. I will give you instructions to begin at the end of five minutes.

Your five minutes starts now.

at the end of 5 min **Do you have any questions?**

Record if any.

You may start now. Remember your goal is to generate as many solutions as possible and the participant with greatest number of solutions will win the prize.

at the end of 1 hour **Please stop the idea generation now. Please mark any analogies that you used to solve this problem. You can circle the parts of your sketches, write a description or both.**

You may take a 5 min break now. The restrooms are outside this room on the other side and there is a water fountain around the corner. Please be back on time.

3. *Design problem 2*

Welcome back. Let us start your second task of the day. Please take the sheets of paper on the upper left corner of the table, turn them over. You will find your new design problem. You will get 45 minutes to generate solutions for this design problem. Try to generate as many solutions as possible to solve this design problem. Please read the problem. If you have any questions, please let me know.

at the end of 1 hours 55 min **Please stop the idea generation. You may take another 5 min break now.**

4. *Design problem 3*

You are about to begin your last task of the day. Please take the sheets of paper on the upper left corner of the table, turn them over. You will find your last design problem. You will get 45 minutes to generate solutions for this design problem. Again, try to generate as many solutions as possible to solve this design problem. Please read the problem. If you have any questions, please let me know

at 2 hours and 50 min **Please stop the idea generation.**

5. *Disbursement*

To improve this experiment, I would like to ask you couple of questions.

Were the design problem and the example clear to you?

Do you have any comments to improve the experiments?

Before you leave, I want one more piece of information from you. What is your major?

Thank you for your participation. Here is the voucher with your payment information. This concludes your portion of the study. Please remember to not discuss this study with

your classmates until after September 1, 2012 since this will bias the data. If you have any questions about this study I can answer them at this time. "

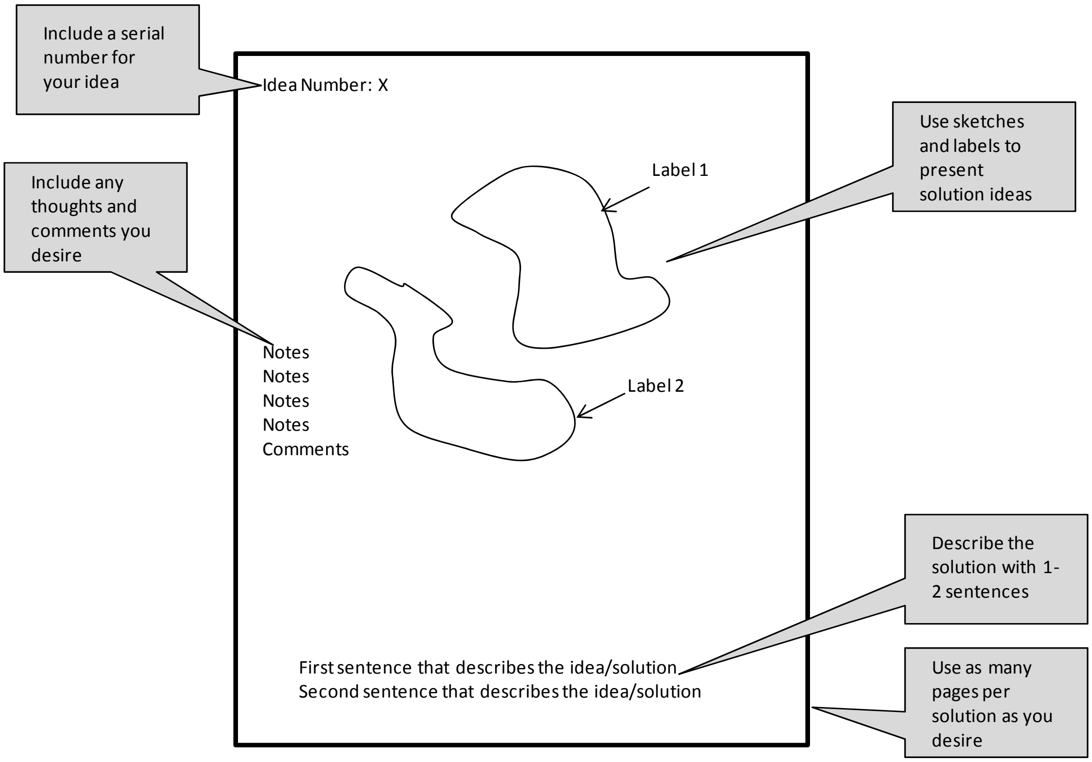
2. Experiment Materials – Control Group

Instructions

Consider the design problem on the following page. Please read these instructions and the design problem description carefully. You will be given up to 5 minutes to read this information, followed by 45 minutes to create design solutions to the design problem. Your goal is to create ***as many solutions to the problem as possible***.

Use provided sheets of paper to record your solutions. Each solution should be on a separate page. Your pen will be exchanged at regular intervals to keep track of when the ideas are generated.

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 as you develop each solution."



Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal 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.

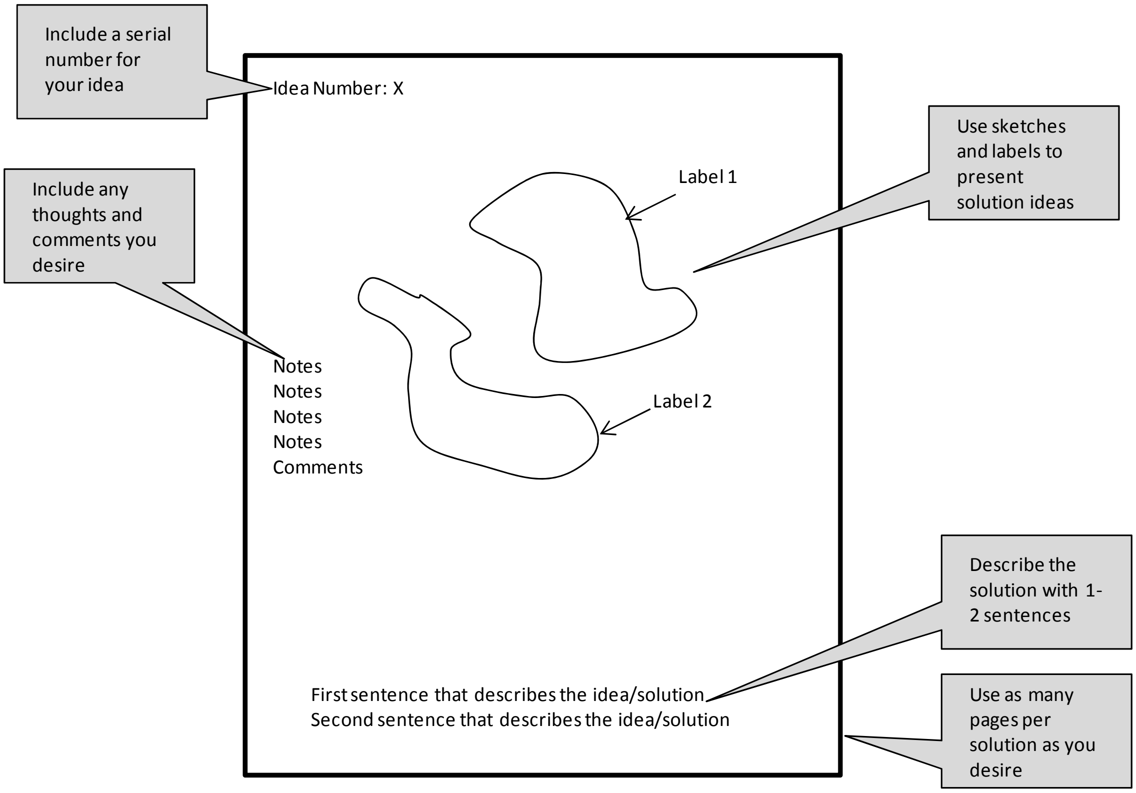
3. Experiment Materials – Pictorial Example Group

Instructions

Consider the design problem on the following page. Please read these instructions and the design problem description carefully. You will be given up to 5 minutes to read this information, followed by 45 minutes to create design solutions to the design problem. Your goal is to create ***as many solutions to the problem as possible***.

Use provided sheets of paper to record your solutions. Each solution should be on a separate page. Your pen will be exchanged at regular intervals to keep track of when the ideas are generated.

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 as you develop each solution."



Design Problem - Device to Shell Peanuts

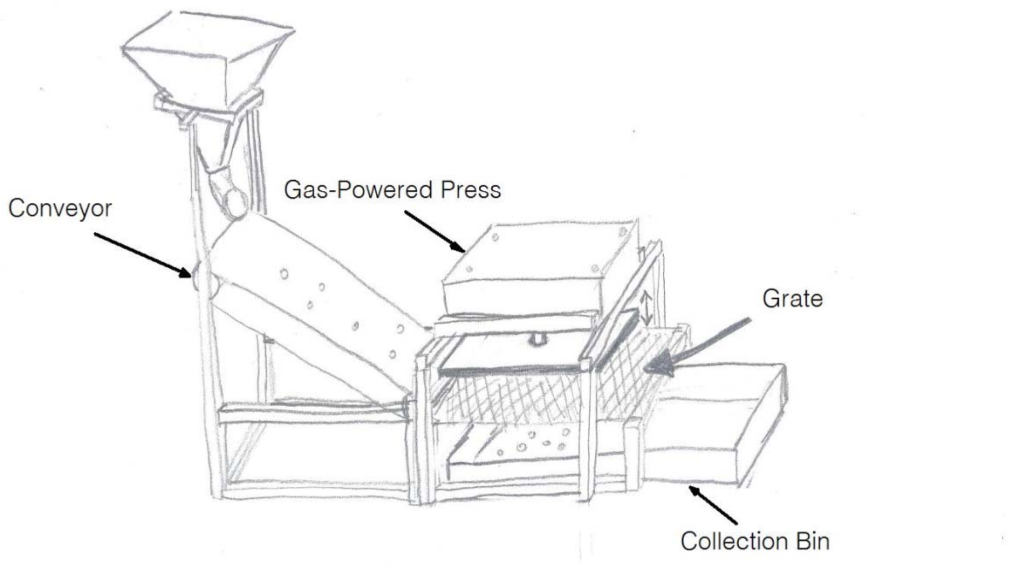
Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal 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.

Consider the following solution as an example that might be created for this design problem.



Solution Description: This system uses a gas powered press to crush the peanut shell. The shell and peanut then fall into a collection bin.

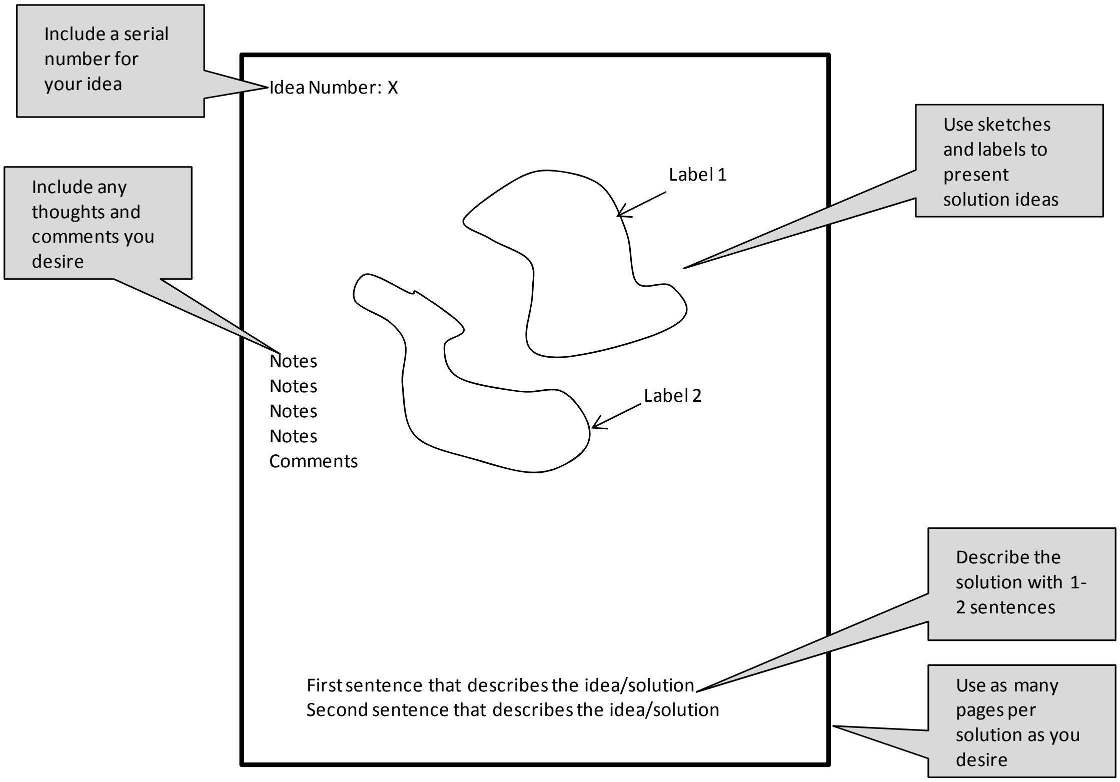
4. <u>Experiment Materials – Physical Example Group</u>

Instructions

Consider the design problem on the following page. Please read these instructions and the design problem description carefully. You will be given up to 5 minutes to read this information, followed by 45 minutes to create design solutions to the design problem. Your goal is to create ***as many solutions to the problem as possible***.

Use provided sheets of paper to record your solutions. Each solution should be on a separate page. Your pen will be exchanged at regular intervals to keep track of when the ideas are generated.

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 as you develop each solution."



Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal 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.

A prototype of an example solution to this problem is in front of you. This system uses a gas powered press to crush the peanut shell. The peanuts are fed through the hopper and guided to the grate with a conveyor system. After crushed by the press, the shell and peanut fall into a collection bin.

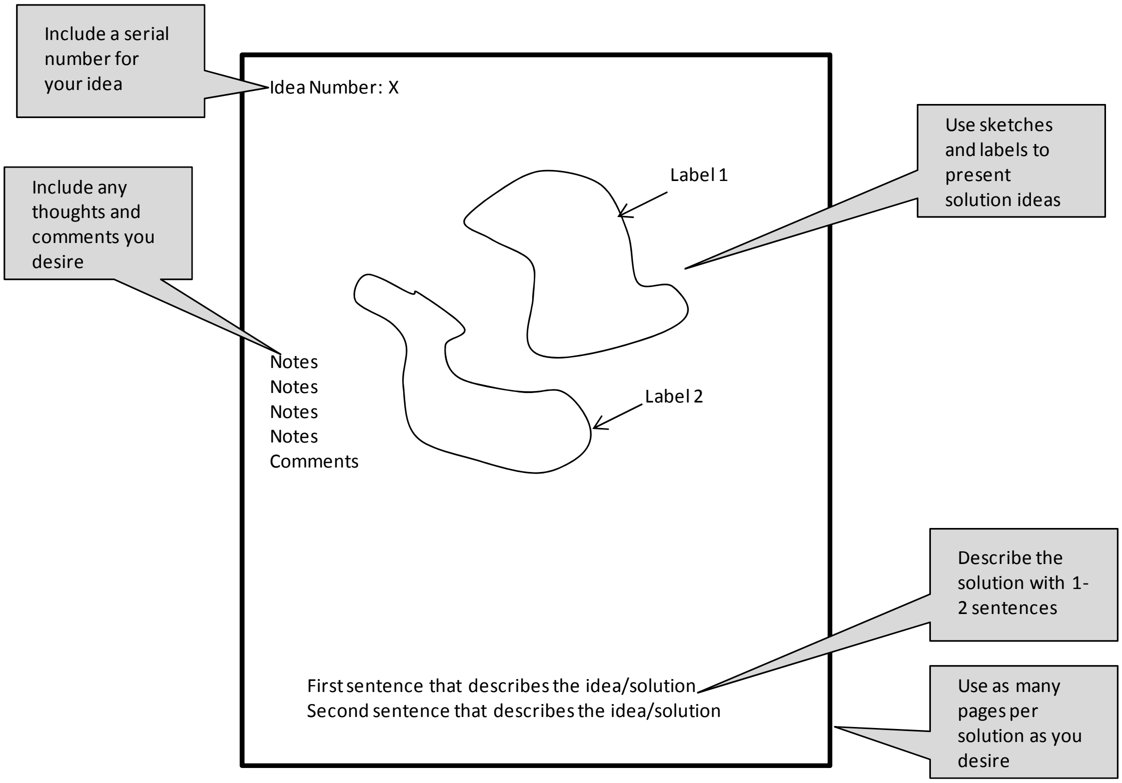
5. Experiment Materials – Pictorial Example Defixation Group

Instructions

Consider the design problem on the following page. Please read these instructions and the design problem description carefully. You will be given up to 5 minutes to read this information, followed by 45 minutes to create design solutions to the design problem. Your goal is to create ***as many solutions to the problem as possible***.

Use provided sheets of paper to record your solutions. Each solution should be on a separate page. Your pen will be exchanged at regular intervals to keep track of when the ideas are generated.

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 as you develop each solution."



Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal 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.

A prototype of an example solution to this problem is in front of you. This system uses a gas powered press to crush the peanut shell. The peanuts are fed through the hopper and guided to the grate with a conveyor system. After crushed by the press, the shell and peanut fall into a collection bin.

To assist you in developing as many designs as possible, consider the following clarification to the problem:

Functions:

- Import natural or human energy to the system
- Convert and transmit energy to peanut
- Remove peanut shell (remove outer structure from inner material)
- Separate removed shell (outer structure) from peanut (inner material)

Example Analogies that You Might Find Helpful:

- Hull
- Shuck
- Husk
- Clean (clean a deer, clean a fish or scale a fish)
- Soak
- Heat, Roast
- Dissolve
- Pod
- Pit, stone
- Burr (deburr something)
- Ream
- Bark (bark a tree)
- Skin
- Pare apples
- Pluck, deplume (strip feathers)
- Peel
- Grind (like a nut grinder)
- Brittle fracture

Natural Energy Sources Available:

- Wind
- Solar
- Running water streams
- Captured rain water at a height
- Solar
- Human
- Animal

Back-of-the-envelope Calculations:

A quick analysis shows that a much greater quantity of power (or force) is needed to act on many peanuts simultaneously compared to applying power to a few peanuts at a time.

6. <u>Sample Concepts Generated by Participants</u>

1)

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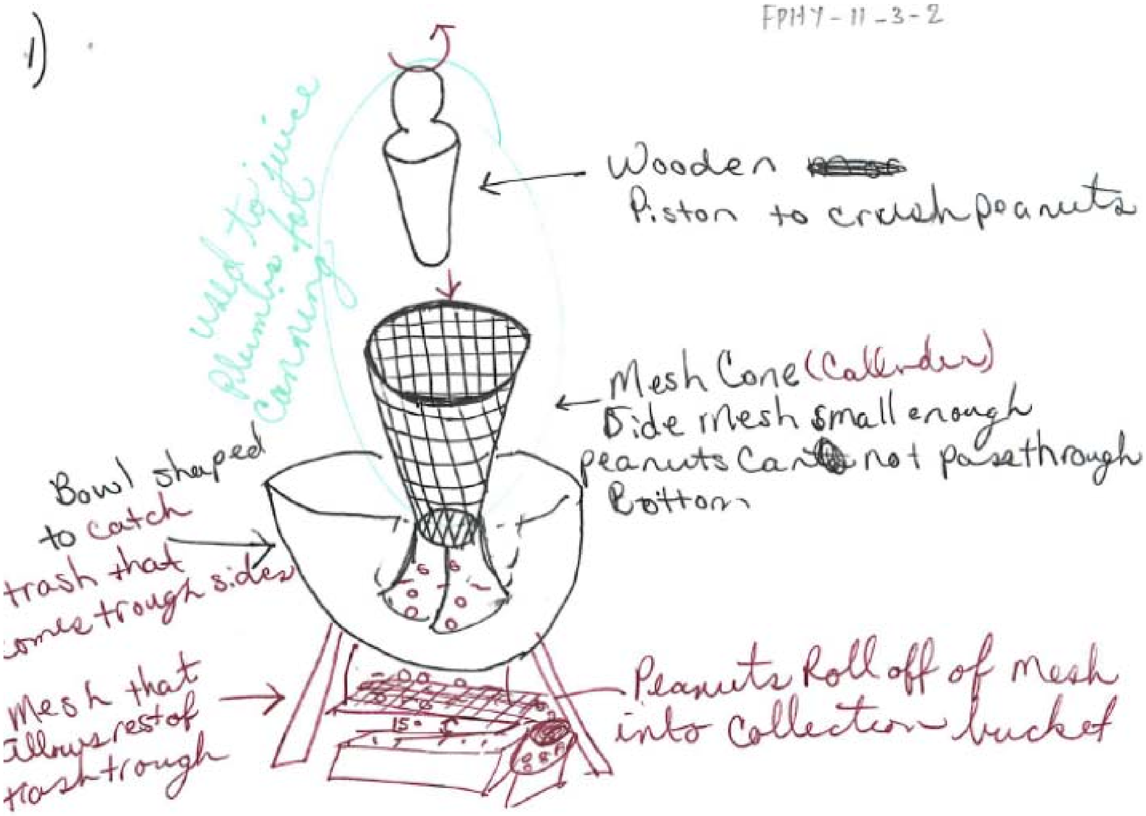
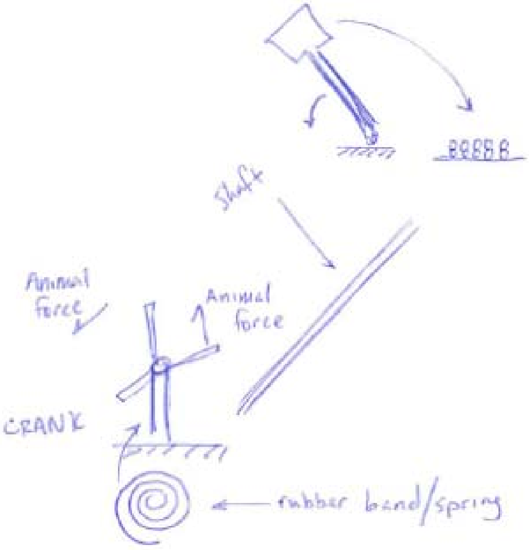
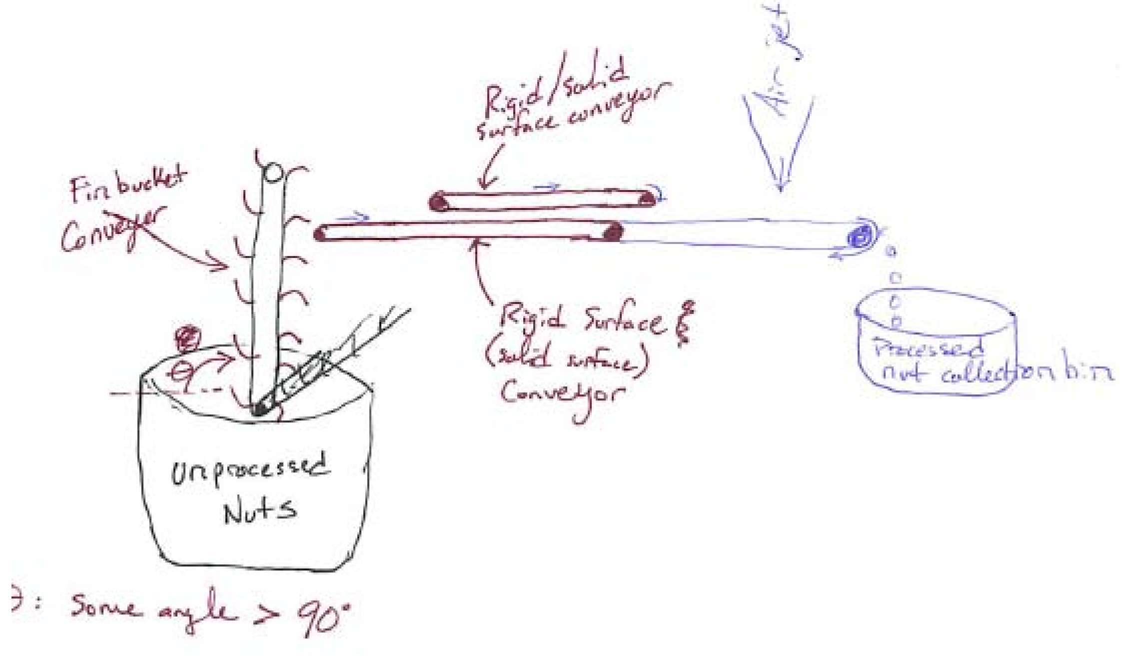
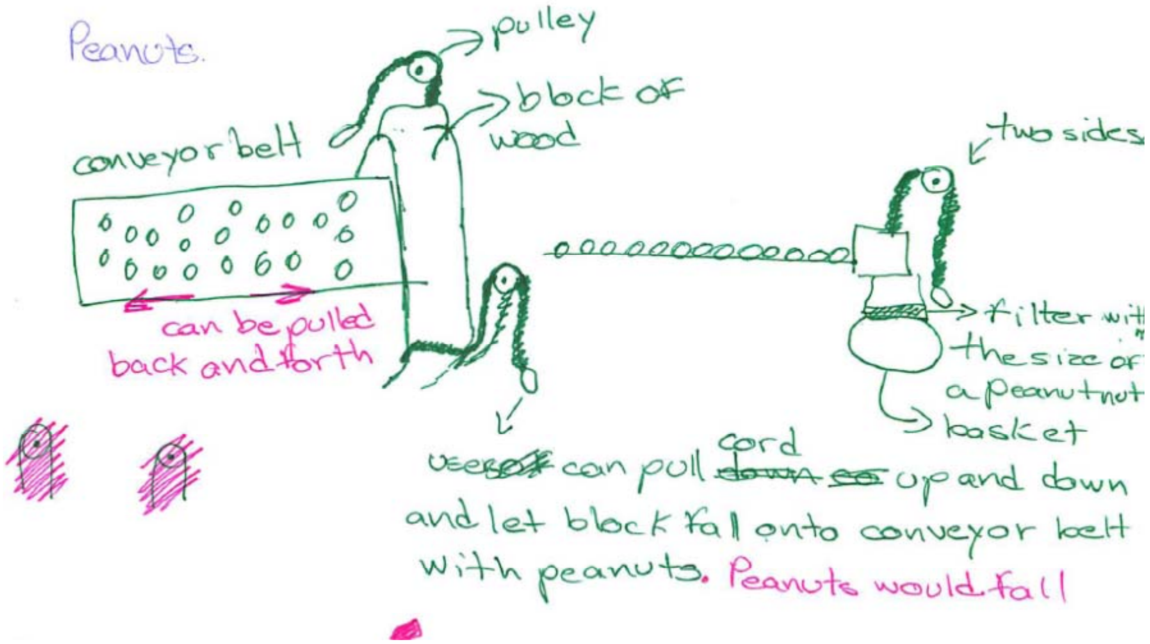


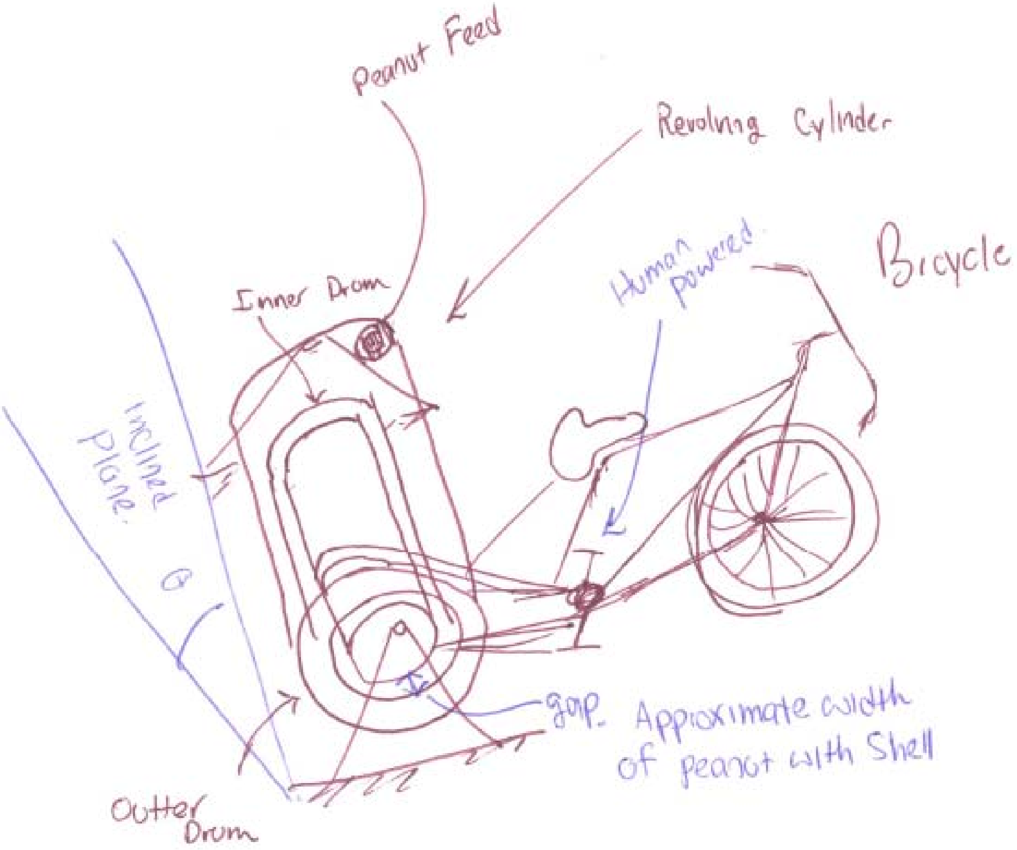


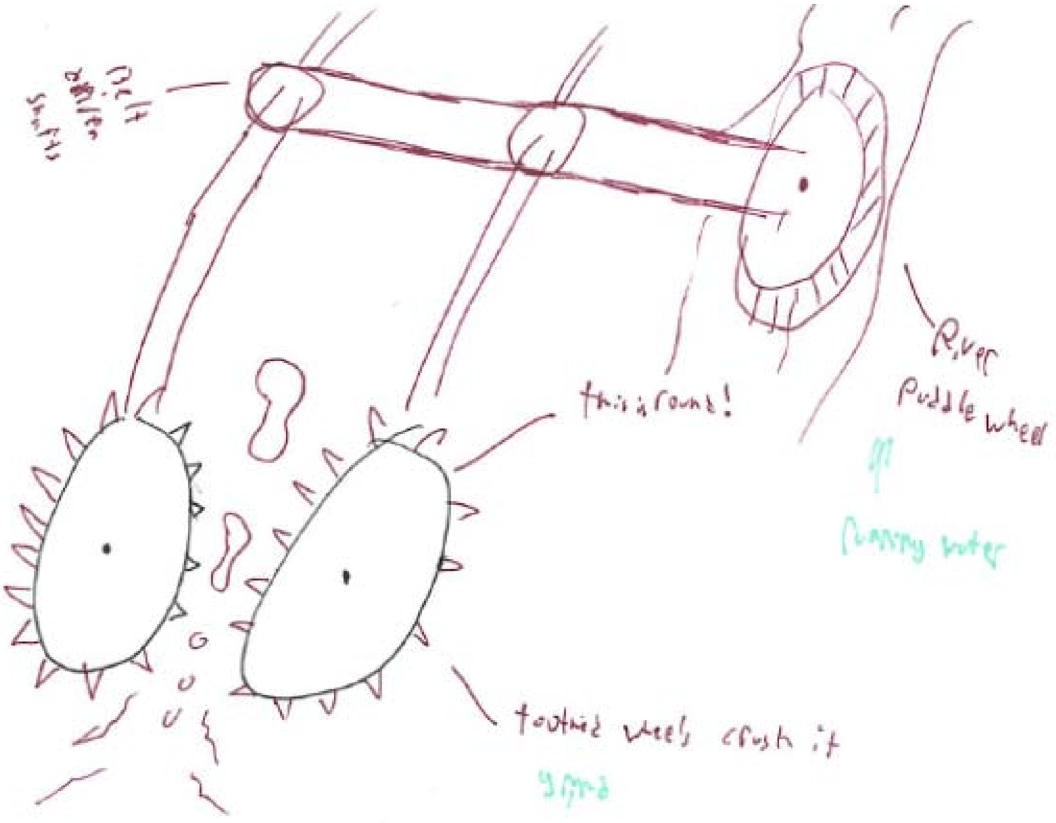


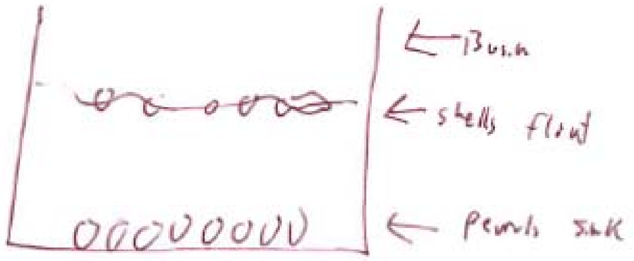
θ: Some angle > 90°



user~~s~~ can pull cord ~~down so~~ up and down and let block fall onto conveyor belt with peanuts. Peanuts would fall


Peanut Feed
Revolving Cylinder
Inner Drum
Human powered.
Bicycle
Inclined Plane.
θ
gap. Approximate width of peanut with Shell
Outter Drum


Belt driven shafts
this is round!
River
Puddle wheel
running water
toothed weels crush it
grind


← Basin
← shells float
← Pearls sink

APPENDIX H

RELATED TECHNICAL PUBLICATIONS

1. Viswanathan, V., Linsey, J., "Physical Models and Design Thinking: A Study of Functionality, Novelty and Variety of Ideas", ASME Transactions: Journal of Mechanical Design *(In Press).*
2. Viswanathan, V., Linsey, J., "Design Fixation and its Mitigation: a Study on the Role of Expertise", ASME Transactions: Journal of Mechanical Design *(In Review).*
3. Viswanathan, V., Linsey, J., " The Role of Sunk Cost in Engineering Idea Generation: An Experimental Investigation", Design Studies *(In prep.).*
4. Viswanathan, V. and Linsey, J., 2012, "Physical Modeling in Design Projects: Development and Testing of a New Design Method," ASEE/IEEE Frontiers in Education Conference, Seattle, WA.
5. Viswanathan, V. and Linsey, J., 2012, "Physical Examples in Engineering Idea Generation: An Experimental Investigation," International Conference on Design Creativity (ICDC2012), Glasgow, UK.
6. Viswanathan, V. and Linsey, J., 2012, "A Study on the Role of Expertise in Design Fixation and its Mitigation", 2012 ASME IDETC – Design Theory and Methodology Conference, Chicago, IL.
7. Viswanathan, V., Esposito, N. and Linsey, J., 2012, "Training Tomorrow's Designers: a Study on Design Fixation", ASEE Annual Conference 2012, San Antonio, TX.
8. Viswanathan, V. and Linsey J., 2012, "Build to Learn: Effective Strategies to Train Tomorrow's Designers", ASEE Annual Conference 2012, San Antonio, TX.
9. Viswanathan, V., and Linsey, J., 2011, "Understanding Physical Models in Design Cognition: A Triangulation of Qualitative and Laboratory Studies", ASEE/IEEE Frontiers in Education Conference, Rapid City, SD.
10. Viswanathan, V., and Linsey, J., 2011, "Design Fixation in Physical Modeling: An Investigation on the Role of Sunk Cost", ASME IDETC-Design Theory and Methodology Conference, Washington, DC.
11. Viswanathan, V., and Linsey, J., 2011, "Understanding Fixation: A Study on the Role of Expertise" International Conference on Engineering Design, Kobenhavn, Denmark.

12. Viswanathan, V., and Linsey, J., 2011, "Physical Models and Design Cognition: Triangulating Controlled Lab Studies with Industrial Case Studies", International Conference on Research into Design, Bangalore, India.
13. Linsey, J. and Viswanathan, V., 2011, "Enhancing Engineering Innovation through Physical Representation", NSF CMMI Research and Innovation Conference, Atlanta, GA.
14. Viswanathan, V., and Linsey, J. , 2010, “Work in Progress – Understanding Design Fixation: A Sunk Cost Perspective on Innovation,” ASEE/IEEE Frontiers in Education Conference, Washington, D.C.
15. Viswanathan, V., and Linsey, J., 2010, “Physical Models in the Idea Generation Process: Hindrance or Help?” Proceedings of the 2010 ASME IDETC-Design Theory and Methodology Conference, Montreal, Quebec, Canada.
16. Viswanathan, V., and Linsey, J., 2009, “Enhancing Student Innovation: Physical Models in the Idea Generation Process,” ASEE/IEEE Frontiers in Education Conference, San Antonio, TX.