EXPLORING TWO PHASES OF DESIGN-BY-ANALOGY "MULTIPLE SOLUTIONS" AND "MULTIPLE ANALOGIES"

A Thesis

by

APEKSHA GADWAL

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

MASTER OF SCIENCE

August 2010

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,   Julie Linsey
Committee Members,   Daniel McAdams
    Steven Smith
Head of Department,   Dennis O'Neal

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ABSTRACT

Exploring Two Phases of Design-by-Analogy "Multiple Solutions" and "Multiple

Analogies." (August 2010)

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India

Chair of Advisory Committee: Dr. Julie Linsey

Idea generation and design-by-analogy are core parts of design. Designers need tools to assist them in developing creative and innovative ideas. Analogy is one such tool that helps designers solve design problems. It is a stimulus that helps generate innovative solutions to a design problem. It is used to generate novel ideas by transferring information (i.e. mapping elements) from a known domain (base) to an unknown domain (target). Multiple solutions can be developed based on a single analog and designers derive principles of design from the analogs (products) they experience. There is little research that discusses creating multiple solutions from a single analog or how multiple analogs can assist designers in mapping high level principles of design.

Multiple paths are available to improve the design-by-analogy process and help designers understand the process better. This thesis explores two phases of design-by-analogy in which designers have difficulty generating multiple inferences from a single source analog and identifying high level principles given multiple example analogs in the presence of noise. Two hypotheses are proposed to explore the importance of analogies in design. 1. A lone designer is able to generate multiple inferences from a

single source analog when instructed to do so. 2. The mapping of high level principles increases with the increase in the number of example analogs and decreases with the amount of noise. Two experiments, "Multiple Solutions" and "Multiple Analogies" are conducted to answer the proposed research questions and to understand how designers can become better analogical reasoners.

The results from the "Multiple Solutions" experiment show that engineers, when directed to, can create multiple solutions from a single analog. Results from the "Multiple Analogies" experiment also satisfy the hypothesis that the mapping of high level principles increases with an increase in the number of analogs and decreases with distracters. A significant interaction is also observed between these two factors. The results indicate more future work with a greater sample size.

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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 and Dr. Smith, for their support.

I am grateful to all the students who participated in my study. This would not have been possible without them. I would like to thank my lab mates 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.

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CHAPTER I

INTRODUCTION: ANALOGY AND INNOVATION

Innovation is what drives the field of new product development. It is essential for the design of new products. Although some believed that creativity cannot be invoked on demand, presentation of appropriate stimuli greatly enhances the generation of concepts (Mak & Shu, 2004). Analogy is one type of appropriate stimuli that aids in generating new ideas (Ahmed & Christensen, 2009; Casakin & Goldschmidt, 1999; Christensen & Schunn, 2007; Dunbar, 1997; Leclercq & Heylighen, 2002). Analogy acts as a stimulus to generate new concepts and solve design problems. It can trigger breakthrough ideas (Herstatt & Kalogerakis, 2005). Using an analogy to solve design problems helps generate innovative and creative solutions. Use of analogies to solve design problems (applying previous knowledge of something) helps designers reason through their designs more easily (Daugherty & Mentzer, 2008). There have been many instances where analogies have led to breakthrough innovations, for example design of Velcro was developed based on an analogy to burrs and design of Speedo swimsuit was inspired from the design of shark skin (page 5).

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This thesis follows the style of *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing*.

Design problem solving is an integral component of engineering and understanding how engineering designers store and retrieve knowledge during the design process is very important. Casakin & Goldschmidt (1999) and Christensen & Schunn (2007) demonstrate that designers frequently retrieve and use solutions from analogous designs to help them create innovative solutions to new problems. Although there have been many studies on analogies in design, there is more to explore in this filed.

Prior research has shown the influence of analogies on design and their significance as a tool for solving design problems. Herstatt and Kalogerakis showed that analogies can be systematically used for breakthrough innovations. They focused on the present approaches such as Synetics, Triz, etc. available to solve design problems and also discussed about organizational mechanisms supporting the use of analogies for breakthrough innovations (Herstatt & Kalogerakis, 2005). Linsey, et al, focused on the effects of representation in sketching, functional models and retrieval and use of analogies. The results from this study showed that representation of the design problem effects what analogies designers retrieve to develop a solution and that design problem representation and memory representation significantly affect the designers' ability. (Linsey et al., 2008). The study by Daugherty and Mentzer discussed about the importance of analogical reasoning in engineering design and its application in technological education. They discussed the existing cognitive theories showing the significance of analogies in design and also emphasized the use of analogies in technical education (Daugherty & Mentzer, 2008).

Previous studies talked about the different types of analogies like close domain and distant domain analogies and when to use which type of analogy (Christensen & Schunn, 2007). Some studies have discussed the importance of analogies in retrieval of knowledge from prior experiences to solve design problems (Linsey et al., 2008). But there are still many unanswered questions related to analogical design. This Thesis aims at answering a few questions related to design–by-analogy and helping designers become better reasoners.

Motivation

Design-by-analogy is a very popular method in the field of innovation and new product development. In the past analogies have inspired and brought about many new concepts and products. For example, the development of the airplane was inspired from birds' wings. The Bionic concept car was based on an analogy to boxfish and an innovative ship sail was based on a bat's wings (Table 1). This shows that analogies play an important role in the early phases of design and help designers generate innovative solutions (Figure 1). As mentioned in the previous section, there have been various studies showing the significance of analogies in design. There is little information available on generating more than one inference from a single analog or on the use of multiple analogs.
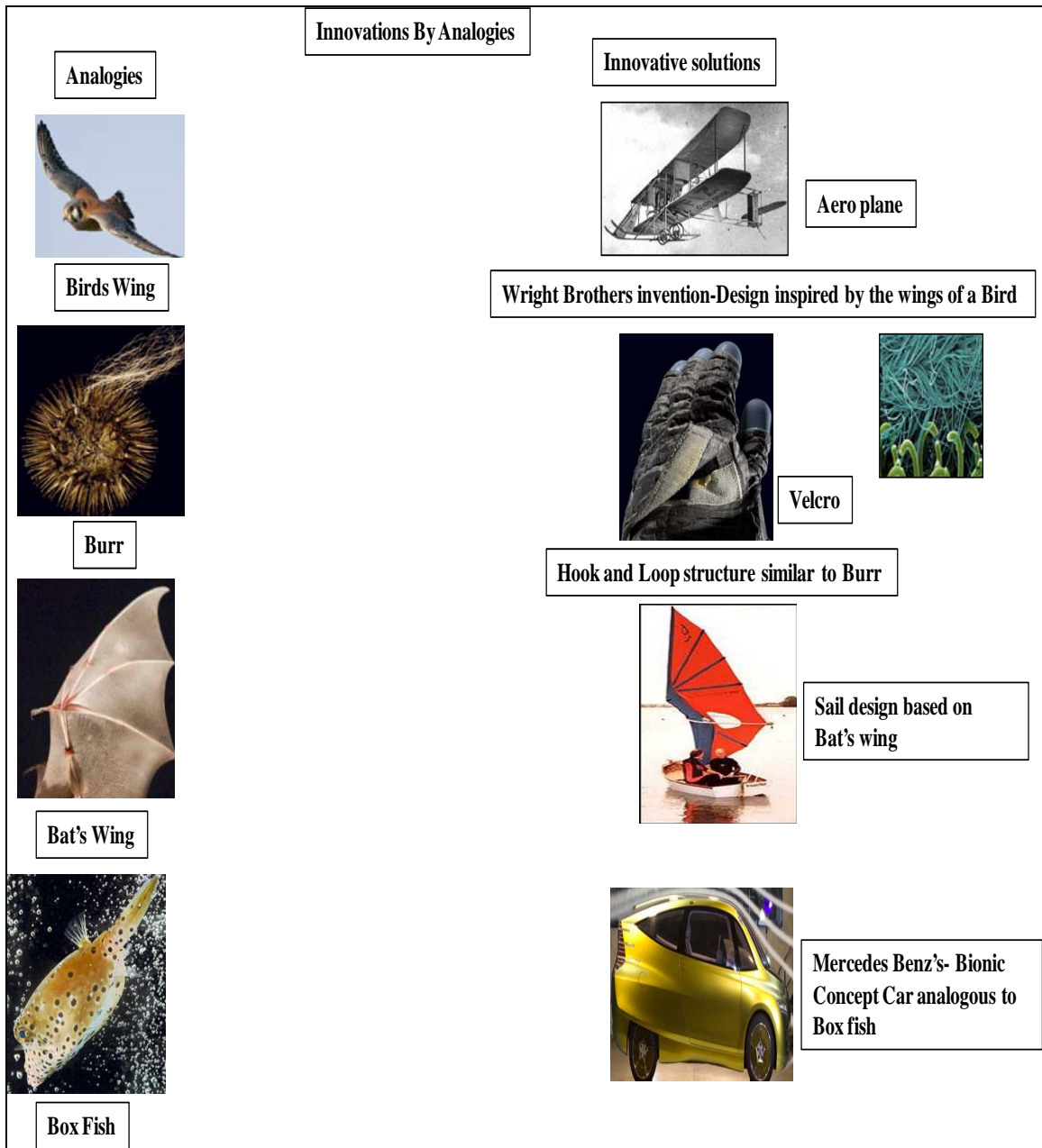
Fig. 1. Innovations Inspired by Analogies

Table 1. List of Sources for Innovations Inspired by Analogies

	Source of Information
1	"National Geographic", http://ngm.nationalgeographic.com/2008/04/biomimetics/clark-photography, <02/16/2010>
2	"Today at brown", http://today.brown.edu/articles/2008/11/bat-flight, <02/16/2010>
3	"bbc news", http://news.bbc.co.uk/2/hi/science/nature/1011107.stm, <02/16/2010>
4	"pbase galleries forum search", http://www.pbase.com/raymondjbarlow/image/106669432, <02/16/2010>
5	"About.com: Inventors", http://inventors.about.com/library/inventors/bl_wright_brothers.htm, <02/16/2010>

There are a number of examples collected as a part of this research where a single analog has inspired multiple innovations. For example consider the "Lotus Effect" analogy (Figure 2), (Table 2). The Lotus leaf is the base analog and the various solutions (products) developed based on this analog are "Lotusan Paint", wiperless windshield, water repelling roof tiles, nanotech clothing fabric and many more as shown in the figure below. All these products map different features from the source analog, but have the same end effect i.e. all have water (liquid) repelling surfaces. A "Gecko's Foot" is another example which has inspired multiple solutions and often for the same problem (Figure 3 on page 10), (Table 3 on page 12). Figure 4 (on page 11) shows the different products developed based on an analogy to a Gecko's Foot. A Gecko's Foot is the source analog and the different solutions developed based on this analog to solve the wall climbing device design problem are a wall climbing robot, magnetic grips and tires.
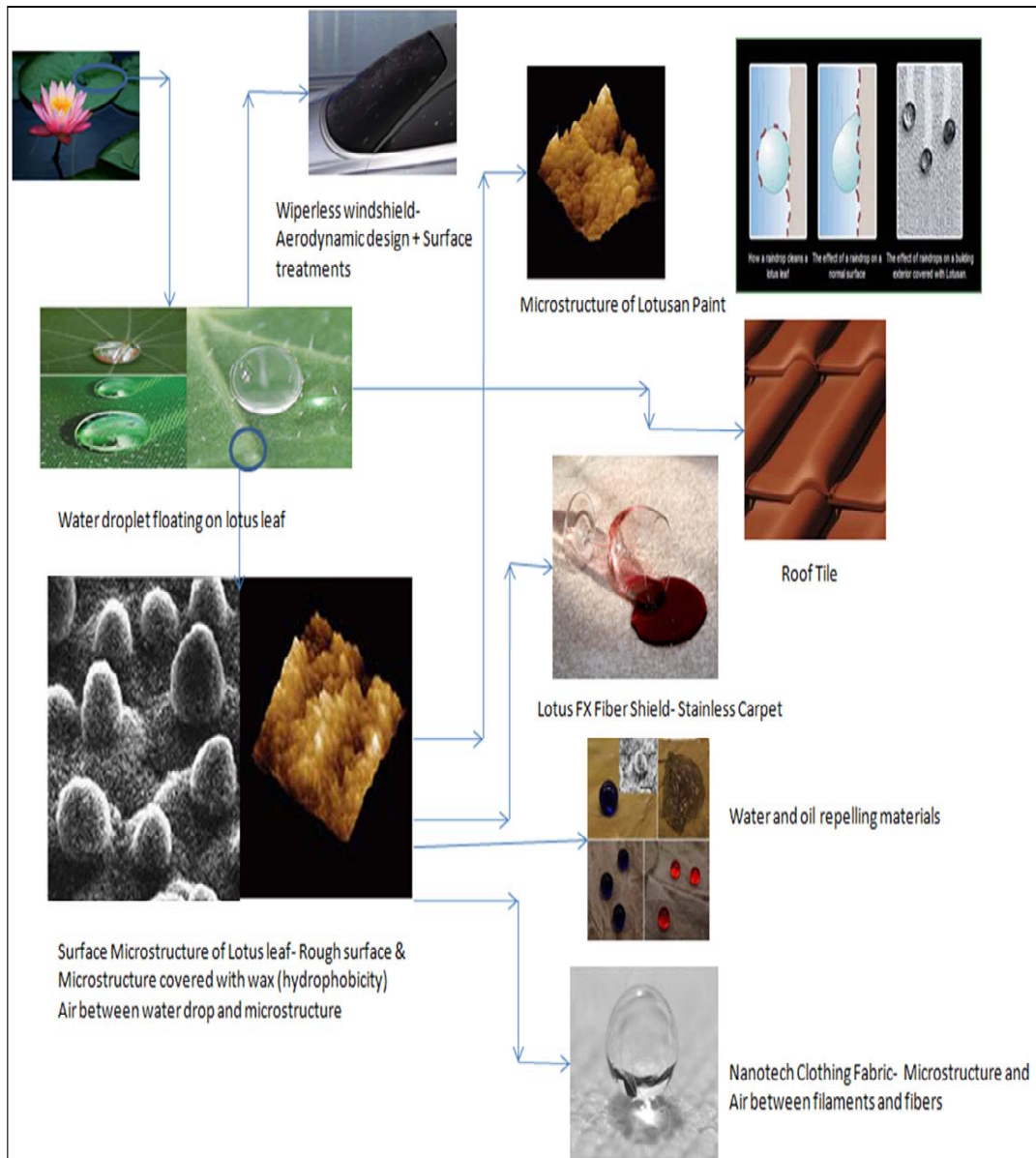
Fig. 2. Multiple Solutions Developed Based on "Lotus Effect" Analogy
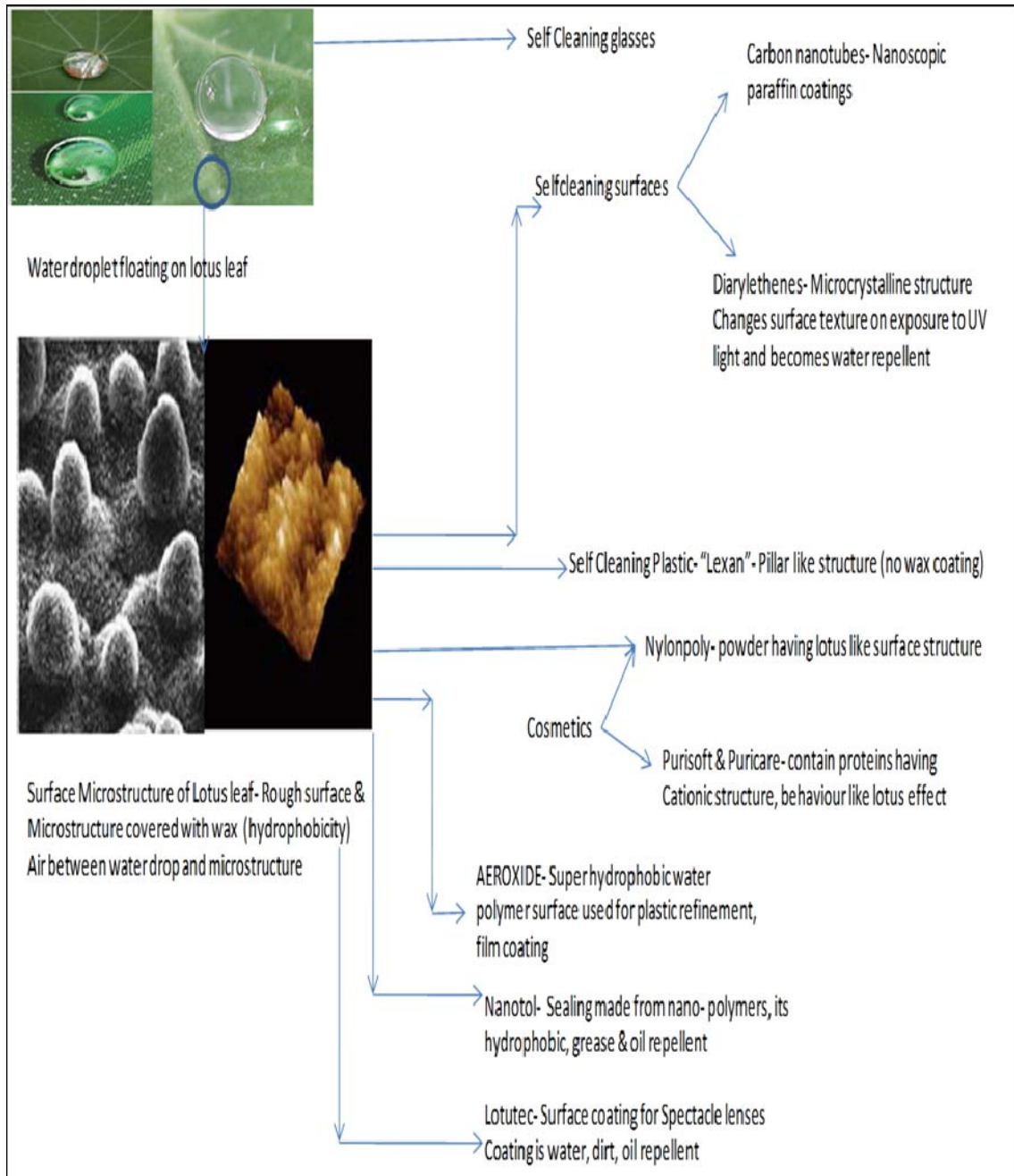
Fig. 2. Continued

Table 2. List of Sources for the "Lotus Effect" Example

	Source of information
1	"Teach English in Asia-Asian Water Lillies and Lotus Flowers", http://www.teachenglishinasia.net/asiablog/asian-water-lilies-and-lotus-flowers, <02/16/2010>
2	"PERCENTA AG Nanotechnology Solutions", http://en.percenta.com/nanotechnology-lotus-effect.php, <02/16/2010>
3	"Nano Canada Painting & Coating Co.", http://nanocanada.biz/Technical-Support.php, <02/16/2010>
4	"INVENTORSPOT", http://inventorspot.com/articles/inspired_lotus_leaf_lotusan_paint_23083, <02/16/2010>
5	"Design and the universe", http://www.designanduniverse.com/articles/lotusan.php, <02/16/2010>
6	"MyRenoRealEstate.com", http://www.myrenorealestate.com/stainmaster-carpet-warranty.html, <02/16/2010>
7	"The stainmaster carpet difference", http://www.stainmaster.com/sm-difference/sss-lotusfx.html, <02/16/2010>
8	"Newscientist tech", http://www.newscientist.com/article/dn16126-nanotech-clothing-fabric-never-gets-wet.html, <02/16/2010>
9	"Technology Review (published by MIT)", http://www.technologyreview.com/communications/21530/?a=f, <02/16/2010>
10	"Biomimicry news", http://www.biomimicrynews.com/research/Engineers_create_oil-repelling_materials.asp, <02/16/2010>
11	"engadget", http://www.engadget.com/2008/02/24/wiperless-windshields-in-your-future-thanks-nanotech/, <02/16/2010>

Table 2. Continued

	Source of Information
12	"NanoPhos Pinoneering nanotechnology", http://www.nanophos.com/en/SurfaPore_en.html, <02/16/2010>
13	"ERLUS", http://www.erlus-lotus.eu/, <02/16/2010>
14	"ERLUS- Erlus lotus- the self cleaning clay roof", http://www.erlus-lotus.eu/prospektbestellungdach/order/download/838/2/en_lotus.pdf, <02/16/2010>
15	"optics.org", http://optics.org/cws/article/research/25810, <02/16/2010>
16	"Scientific American", http://www.scientificamerican.com/article.cfm?id=self-cleaning-materials, <02/16/2010>
17	"Technology Review (published by MIT)", http://www.technologyreview.com/BizTech-R&D/wtr_16415,295,p1.html, <02/16/2010>
18	"Nylonpoly lotus effect", http://www.prochem.ch/html/forum/flyers/creation_couleur/Nylonpoly_Leaflet_04_EN_m.pdf, <02/16/2010>
19	"Nanoengineered surfaces- Self cleaning coatings", http://www.ngimat.com/pdfs/Nanoengineered_Surfaces_Self_Cleaning.pdf, <02/16/2010>
20	"Progress article-self cleaning surfaces- virtual realities", http://www.iri.cnrs.fr/data/bng/03_blossey_nmat.pdf, <02/16/2010>
21	"Zeiss sports optics", http://www.zeiss.de/C1256BCF0020BE5F/Contents-Frame/628BAFE5A02D67088525725B0039055D, <02/16/2010>
22	"CeNano GmbH & Co.KG", http://www.cenano.de/nanotechnology-products/products-choice/nanotol-the-universal-nano-product/, <02/16/2010>
23	"degussa creating essentials", http://www.protectosil.com/pub/NR/rdonlyres/75F556A3-9505-420F-9617-CB0B085DFB2C/0/Clean_Einzelseiten.pdf,<02/16/2010>
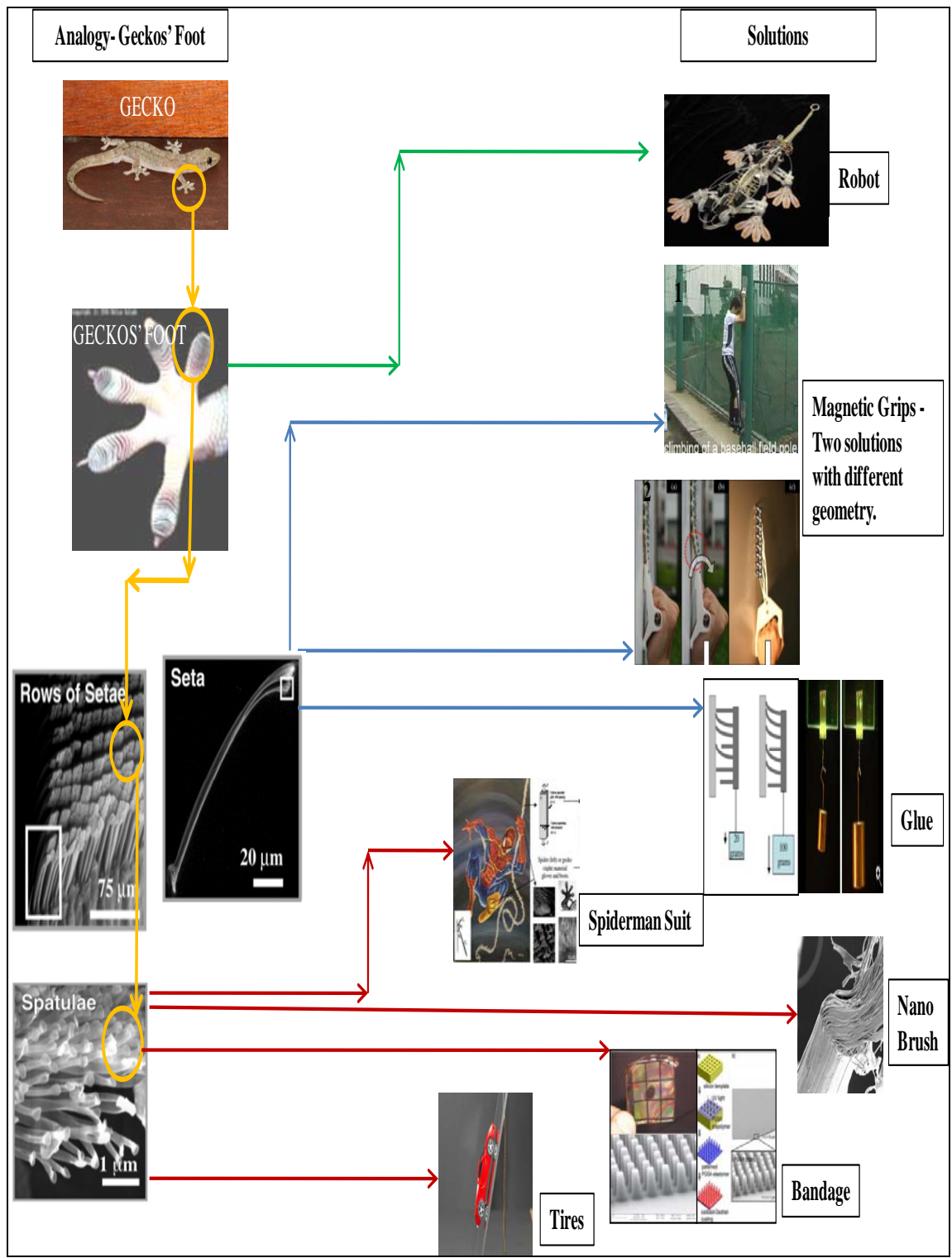
Fig. 3. Multiple Solutions Based on "Gecko's Foot" Analogy
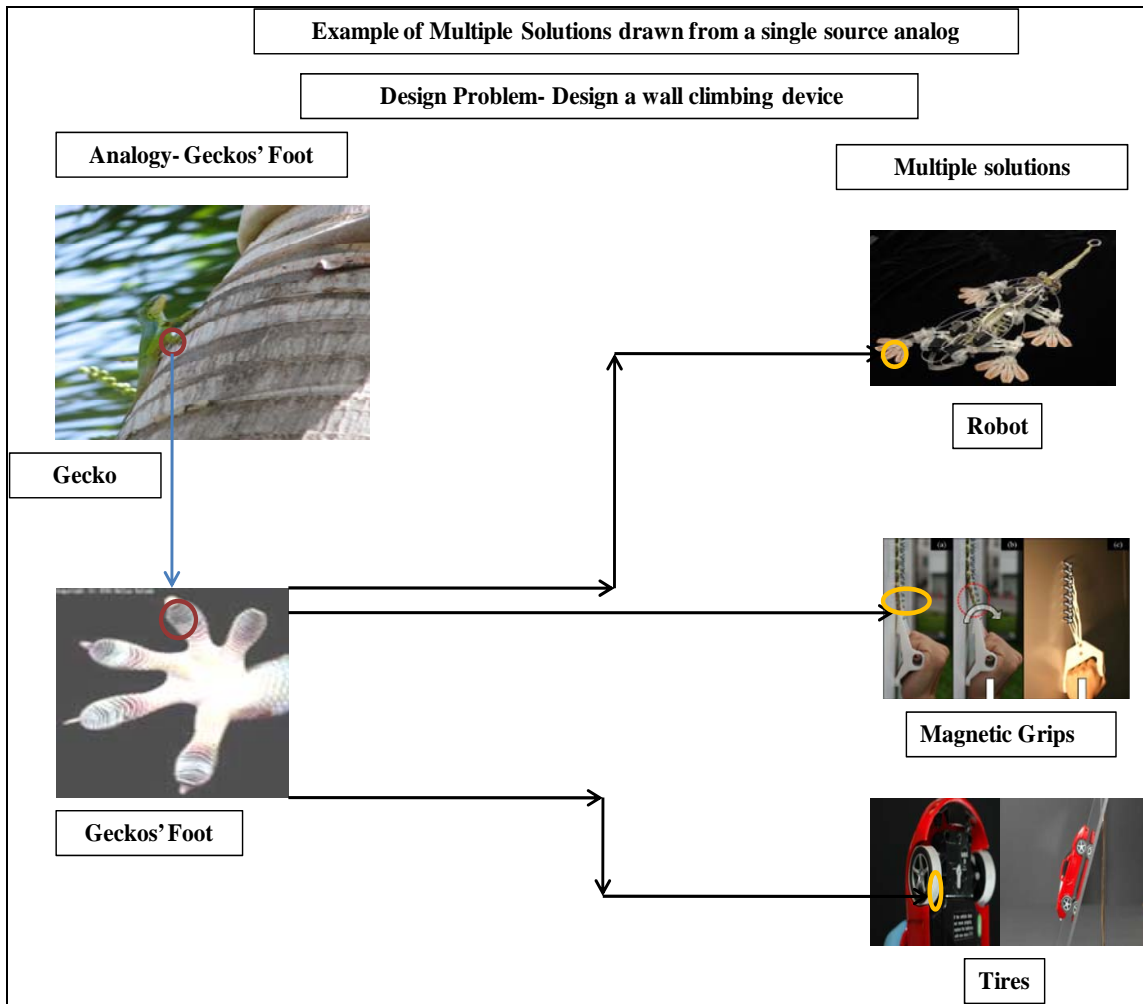
Fig. 4. Multiple Solutions Derived from a Gecko's Foot Analogy for Wall Climbing Device Design

Problem

Table 3. List of Sources for the "Gecko's Foot" Example

	Source of Information
1	"Smart gecko tape", http://robotics.eecs.berkeley.edu/~ronf/Gecko/interface08.html, <02/16/2010>
2	"The Geckos that we keep and breed are as follows", http://www.geckodan.com/geckos.htm, <02/16/2010>
3	"Photobucket", http://s102.photobucket.com/albums/m94/geckodanweb/DtellaHouseGecko.jpg, <02/16/2010>
4	"Designboom", http://www.designboom.com/contemporary/biomimicry.html, <02/16/2010>
5	"Biomimetics & Dextrous Manipulation Laboratory", http://bdml.stanford.edu/twiki/bin/view/Rise/StickyBot, <02/16/2010>
6	"Biomimetics & Dextrous Manipulation Laboratory", http://bdml.stanford.edu/twiki/bin/view/Main, <02/16/2010>
7	"MIT news", http://web.mit.edu/newsoffice/2009/stickybot-092509.html, <02/16/2010>
8	"Invention", http://www.newscientist.com/blog/invention/2007/11/magnetic-gecko-grip.html, <02/16/2010>
9	"IOP electronic journals", http://www.iop.org/EJ/article/1748-3190/2/1/001/bb7_1_001.pdf?request-id=3a212b61-0137-401f-97f7-23c2f1b9a780, <02/16/2010>
10	"Technology review", http://www.technologyreview.com/player/07/04/30Rowe/1.aspx, <02/16/2010>

Table 3. Continued

	Source of information
11	"TED ideas worth spreading", http://www.ted.com/talks/robert_full_learning_from_the_gecko_s_tail.html, <02/16/2010>
12	"IEEExplore digital library", http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4209261&userType=inst, <02/16/2010>
13	"BBC news", http://news.bbc.co.uk/2/hi/6967474.stm, <02/16/2010>
14	"biomimetics millisystems lab, dept of eecs, uc berkeley",http://robotics.eecs.berkeley.edu/~ronf/Gecko/index.html, <02/16/2010>
15	"MIT news", http://web.mit.edu/newsoffice/2008/adhesive-0218.html, <02/16/2010>
16	"Gecko Nano Brush", http://spiedl.aip.org/getpdf/servlet/GetPDFServlet?filetype=pdf&id=PSISDG005925000001592509000001&idtype=cvips&prog=normal, <02/16/2010>
17	"Scientific blogging", http://www.scientificblogging.com/variety_tap/carbon_nanotubes_spiderman_its_all_gecko_to_me, <02/16/2010>
18	"imechanica", http://imechanica.org/node/504, <02/16/2010>
19	"Picasaweb albums", http://picasaweb.google.com/lh/photo/qVmaJ_3ywass-GZUE__-9g, <02/16/2010>
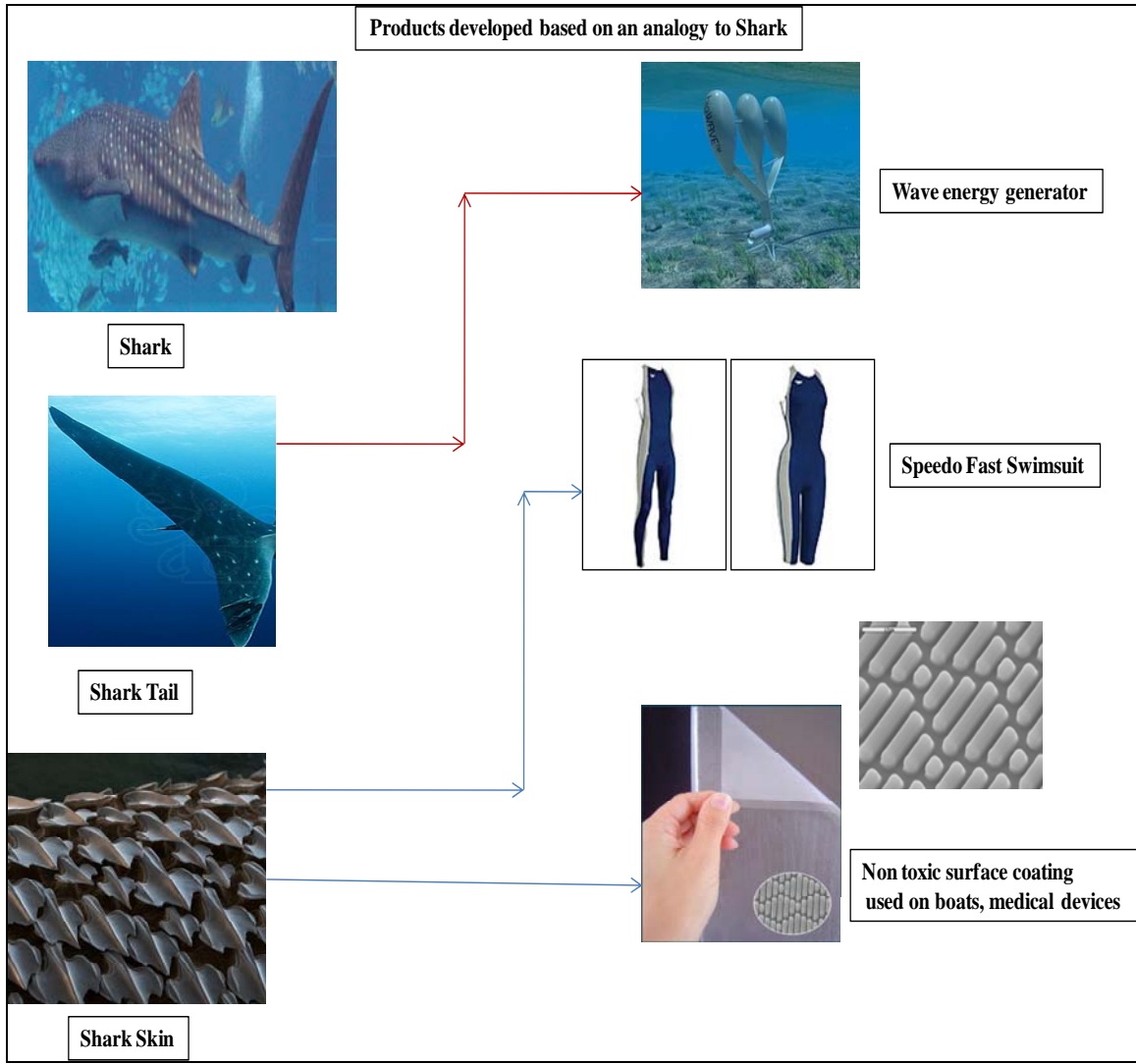
Fig. 5. Multiple Solutions Based on an Analogy- Shark

Table 4. List of Sources for the "Shark" Example

	Source of Information
1	"Biomimicry institute", http://www.biomimicryinstitute.org/home-page-content/home-page-content/biomimicking-sharks.html, <02/16/2010>
2	"crisis fronts", http://crisisfronts.blogspot.com/2008/04/biomimetics-design-by-nature.html, <02/16/2010>
3	"National Geographic", http://ngm.nationalgeographic.com/2008/04/biomimetics/clark-photography, <02/16/2010>
4	"A Schmahl Science Workshop", http://www.schmahlscience.org/blog/?tag=boat-design, <02/16/2010>
5	"gcaptain", http://gcaptain.com/maritime/blog/ocean-kites-top-10-green-ship-designs/, <02/16/2010>
6	"shark skin coating, shenzhen b&b technology", co.ltd, http://www.sharkskincoating.com/newse.asp?newsid=240, <02/16/2010>
7	"v7n", http://www.v7n.com/forums/attachments/forum-lobby/9428d1242310004-your-favorite-animal-whale-shark-aquarium.jpg, <02/16/2010>
8	"shark inspired boat surface", http://www.aip.org/dbis/stories/2005/15008_full.html, <02/16/2010>
9	"discoveries + breakthroughs inside science", http://www.aip.org/dbis/stories/2005/15008.html, <02/16/2010>
10	"The Speedo Fastskin fsii Swimsuitswim faster Story", http://www.swimming-faster.com/, <02/16/2010>

The third example is also an analogy from nature, a Shark. Shark skin has inspired many innovations like the Speedo fast swimsuit, new surface coatings for boats and a wave- energy generator (based on Shark tail) (Figure 5), (Table 4). So it is evident from the above examples that a single analog can inspire multiple solutions, but it is unclear how well a designer can derive multiple inferences.

This observation from these examples leads to the first research question of this thesis: Can multiple solutions be drawn from a single source analog? Also there is little

research that talks about the optimum number of analogs to be used while solving a design problem. Prior studies by Namy and Gentner (2002) and Markman and Gentner (1993) say that presenting two examples is better than one. There is no information available about using more examples or what the effect of the presence of extraneous information would be while solving a design problem. So, the second part of the thesis aims at answering this question regarding the optimum number of examples to be used and how can engineers be more effective at deriving principles of design.

This thesis explores research questions on multiple inferences and multiple analogies. Two separate experiments are conducted for this purpose. In the "Multiple Solutions" experiment subjects were given a design problem with a corresponding analog and asked to generate multiple solutions based on the analog. Prior work shows that creating more than one solution from a single analog is cognitively difficult (Krawczyk et al., 2005) and as described in the reanalysis of prior data in Chapter III participants do not typically attempt it. The "Multiple Analogies" experiment tested the effect of multiple analogs and noise on high level principle mapping. The participants were given a set of products and a design problem. They were then asked to generate ideas for the design problem. The following chapters first describe the foundations in the prior literature and then explain both the experiments and the results in detail.

CHAPTER II

BACKGROUND

This chapter presents relevant research in analogy and design and discusses the significance of analogy in design. Applicable cognitive theories and their implications are also discussed.

Analogical Reasoning and Innovation in Design

Design-by-analogy is a very effective method to come up with innovative and creative solutions (Linsey et al., 2008). Analogical reasoning helps generate novel ideas for a design problem. Innovations inspired from analogies are common in articles, journals and magazines. The studies by Christensen and Schunn (2007), Linsey et al. (2008), Sifonis et al. (2006), Mak and Shu (2004), Herstatt and Kalogerakis (2005), Kalogerakis et al.(2005) and Daugherty and Mentzer (2008) show evidence that designers often use analogies as a tool for innovation. Analogies serve three functions in concept development- identifying the problem, solving the problem and explaining the concept to someone else (Christensen & Schunn, 2007). There are different types of analogies like close domain and distant domain, used for solving design problems. Designers also use their past knowledge as close domain analogies to generate new concepts. Thus, analogical reasoning and design-by-analogy is a powerful tool not just in the initial phases of design, but also helps in process planning, estimating costs and overall new product development (Eckert et al., 2005).

Cognitive Models of Analogical Reasoning

Analogical reasoning is a widely used tool in design cognition. Analogical reasoning is a general human capacity (Holyoak & Thagard, 1996) involved in many domains, mostly in creative fields like design, art and science (Christensen & Schunn, 2007). "Analogy can be viewed as a mapping of knowledge from one situation to another enabled by a supporting system of relations or representations between situations" (Gentner, 1983). Figure 6 shows the various steps involved in reasoning by analogy (Gentner & Markman, 1997). The process of analogical reasoning starts with encoding the source. All the details or information from the source is encoded in memory and then, at a later time, suitable analogs are retrieved. Then relationships or mappings are drawn between the source and the target (design problem) and different solutions (inferences) are developed for the design problem.
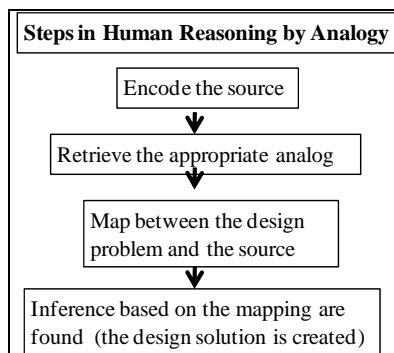
Fig. 6. Steps in Reasoning by Analogy

Structure Mapping Theory and Structural Alignment

Structural alignment is a more detailed description of the underlying process associated with models of analogical reasoning (Falkenhainer et al., 1989; Gentner, 1983; Holyoak & Thagard, 1989). So in structural alignment the target domain is compared with the base domain based on their relational structure. Figure 7 shows a graphical representation of the structure mapping process (Daugherty & Mentzer, 2008).
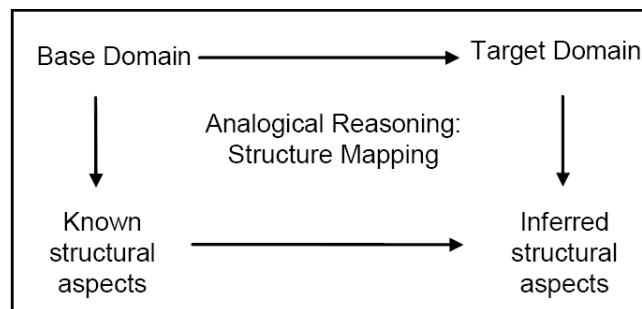
Fig. 7. Graphical Representation Showing the Structure Mapping Process That Explains Analogical Reasoning

The structural alignment view of analogy shows an alignment of relational structure between the base and target domains. This alignment has three constraints to satisfy. 1) Structurally consistent: This implies that the alignment should have parallel connectivity, that is it should be a one-to-one mapping between the base and target (Holyoak & Thagard, 1989). 2) Relational Focus: This means that analogies should have relations in common between the base and target but need not have surface relations. 3) Systematicity: Analogies tend to match connected systems of relations (Falkenhainer et

al., 1989; Gentner, 1983). The structural consistency constraint and relational focus constraint are important for this present study as they talk about maintaining a parallel mapping between the source and target and focus on using relational features to map between the source and target. "A matching set of relations interconnected by higher order constraining relations makes a better analogical match than an equal number of matching relations that are unconnected to each other" (Gentner & Markman, 1997). Figure 8 shows structural alignment process applied to a Gecko's Foot example. This figure is used for the purpose of illustration of the concept of structural alignment between existing solutions and the gecko. To create new solutions, designers structurally align the analog with the design problem (not the solutions) and then inferences are drawn creating new solutions.

One-to-One Mapping Constraint

The fundamental purpose of analogy is to generate plausible and useful inferences (Krawczyk et al., 2005). In order to obtain useful inferences from analogical reasoning, analogical mappings have to be constrained, otherwise too many inferences are possible (Krawczyk et al., 2005). From structural alignment theory, one of the constraints of relational alignment is structural consistency.
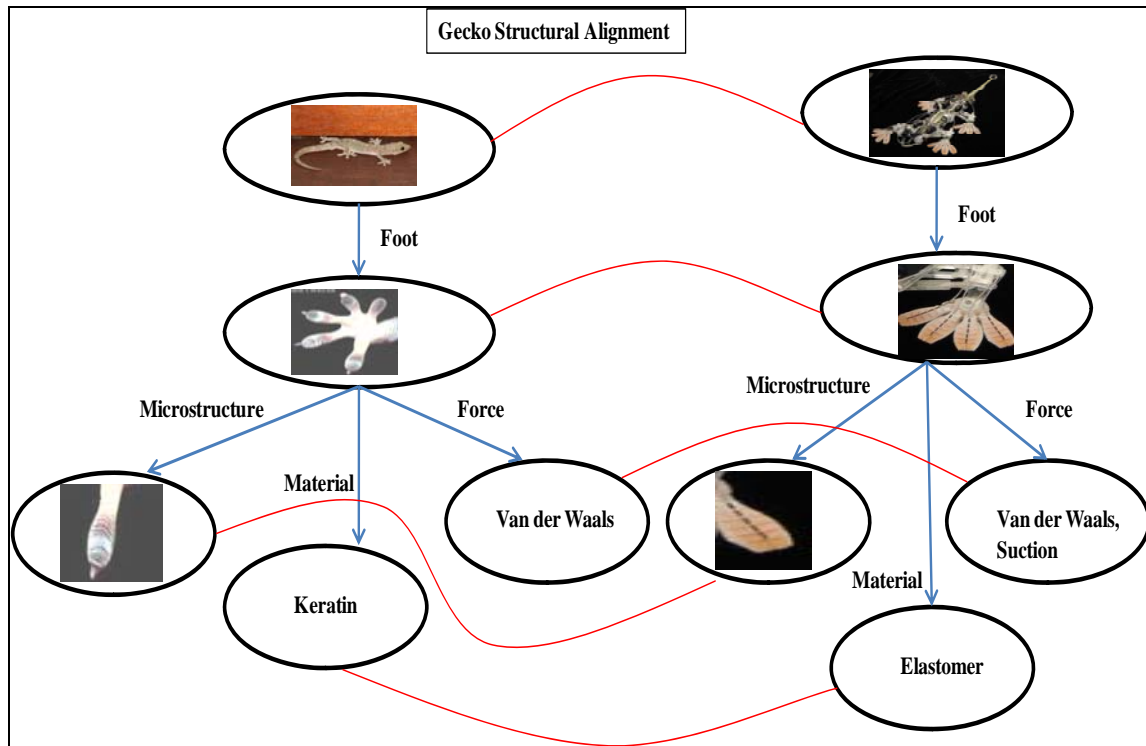
Fig. 8. Example for Illustration Only- Structural Alignment Process Illustrated with a Gecko's Foot and Existing Solutions. This Does Not Illustrate New Solution Creation, Only Structural Alignment Between an Analog and Existing Solutions

The alignment has to be parallel implying that only one-to-one mapping has to exist between the base and target domain. For example, if we consider the above figure showing the relation structure for a Gecko's Foot, the mappings between the source (Gecko's Foot) and the target (Wall Climbing Robot) are parallel. There is only one feature or characteristic mapped between the source and the target. In Holyoak's theory, the basic structural constraint is isomorphism.

Isomorphism means to find structurally consistent mappings, and map elements as one-to-one correspondences (i.e. if a source and target element correspond in one relational role, the same elements should correspond in all relational roles) (Holyoak & Thagard, 1989). This theory says that people generally generate multiple mappings (for example a homomorphic mapping) but find it hard to generate multiple inferences. The one-to-one constraint is because inferences derived using a mix of incompatible element mappings are likely to be incoherent (Falkenhainer et al., 1989; Gentner, 1982; Markman & Gentner, 1997).

There have been theories in analogical reasoning which have assumed that the one-to-one constraint discourages one-to-many mappings from base to target domain (Krawczyk et al., 2005). In contrast it has been found that even though people map one-to-many elements, they find it difficult to generate more than one inference (Krawczyk et al., 2005). Multiple correspondences appear to arise from multiple isomorphic mappings, rather than from a single homomorphic mapping (Krawczyk et al., 2005). Figure 9 shows the isomorphic and homomorphic mappings for a Gecko's Foot example.

As the structural consistency requirement and one-to–one constraint restrict the use of analogies to draw multiple solutions, this leads to the first research question: Can engineers draw multiple solutions (multiple inferences) from a single analog? If so, what types of inferences are typically made from the analog? What inferences are more and less likely to occur? Are relational (functional) or surface features more likely to be mapped?

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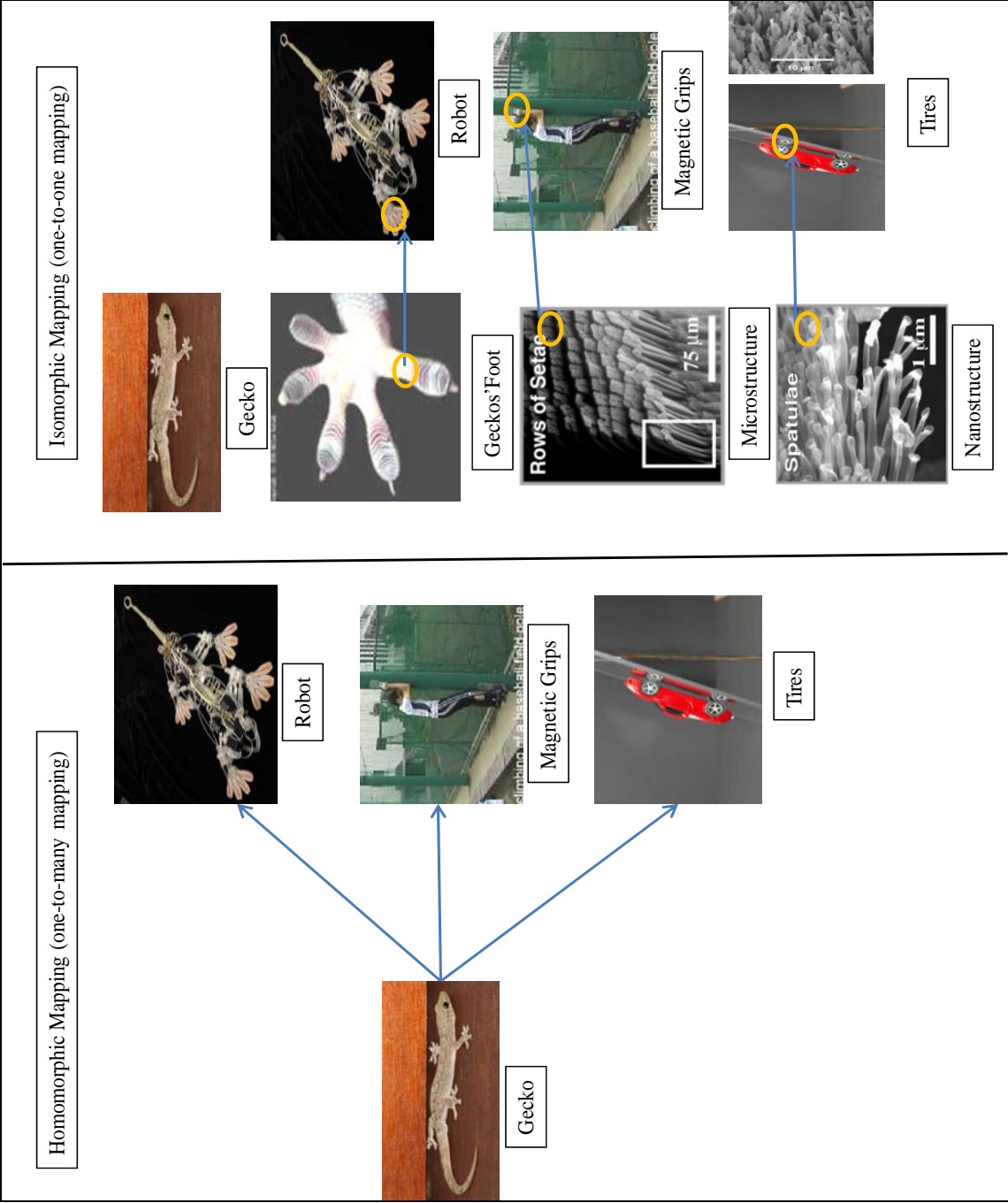
Fig. 9. Isomorphic and Homomorphic Mappings Derived from a Gecko's Foot Analogy

Optimum Number of Analogs to Solve Design Problems

Previous studies by Markman and Gentner (1993), Namy and Gentner (2002) and Gick and Holyoak (1983) have shown that two analogs are better than one to help solve problems. Gick and Holyoak had students solve a difficult design problem. Prior to that, the students were given either one analog to study or two analogs to compare. They found that the students who had two analogs to compare performed better in solving the difficult design problem than students who studied one example. Markman and Gentner found that comparing two analogs helped participants focus more on relational attributes than surface attributes (Markman & Gentner, 1993). Another study by Loewenstein, Thompson and Gentner (1999) also stated that management school students who compared two negotiation scenarios could apply those more correctly to real time situations than students who just studied the same without comparing them. The study by Namy and Gentner (2002) on categorical learning also showed that two examples are better than one. So, all these past studies state that two analogs are better than one in solving design problems. There is no information available about the optimum number of analogs to be used and how this would help designers or what the effect of the presence of noise would be while solving a design problem. The second research question deals with multiple analogs and how effective engineers can be in identifying and mapping high level principles. What causes the high level principles of an analog more likely to be mapped while in the presence of noise products?

CHAPTER III

IDENTIFYING PRINCIPLES FOR GENERATING MULTIPLE SOLUTIONS: REANALYSIS OF A PRIOR ANALOGY EXPERIMENT AND EXISTING EXAMPLES

Overview

The aim of this experiment was to reanalyze the data of a previous analogy experiment (Linsey, 2007) to check if multiple inferences had been drawn for the given design problems based on the analogs. As a follow up task for the prior analogy experiment, a study was done analyzing the solutions generated by the participants for the given two design problems. The study aimed at identifying patterns in the solutions generated. It was to check if the participants had used the analogs to generate multiple solutions and if they had used the analogs what features did they use from the analogs.

The original experiment evaluated the effects of memory and problem representation on design-by-analogy. It studied the effects of representation for both the analog and the design problem. It was conducted as a 2x2 factorial experiment with four different groups. Analogous product representation and design problem representation were the two factors and each had two forms: General and Domain Specific as in Table 5. In all the groups the participants had the same tasks as described in the procedure. The main purpose of these tasks in the prior experiment was to identify factors that helped retrieve previous knowledge (seen analogies) and then use that to solve design problems. From the study it was clear that the representation of the analog and the design problem had an effect on the ability of the designer to use the analog to solve the

design problem. For detailed results please refer to the dissertation by Dr. Julie Linsey (2007).

Table 5. Experimental Conditions for Prior Analogy Experiment

		Analogous product representation	
		General	Domain Specific
Design problem representation	General	Condition 1	Condition 2
	Domain Specific	Condition 3	Condition 4

Method

Participants

The participants were senior Mechanical Engineering students at University of Texas, Austin, who had a course in design methodology and idea generation.

Procedure

The experiment included multiple tasks. The first task was "Memorizing task", where the participants were given descriptions of five products and asked to memorize it. This was followed by a quiz on the memorizing task. The final task was to solve design problems. The participants were given two design problems which had two corresponding analogs in the memorizing task and the participants were asked to generate as many solutions as possible for the design problem. Of all these tasks, only the last task of solving the design problems using the given analogs was important for

the reanalysis. Figure 10 and Figure 11 show the two design problems and the corresponding analogs given to solve the design problems. The figures also include sample solutions generated by the participants.

Metrics

In the reanalysis the metric used was to check whether the participants had drawn multiple inferences from the source analog and if the participants used either surface or functional features from the analog.

Results

The reanalysis of the prior analogy experiment solutions (Figure 10 and Figure 11) showed that participants had not generated multiple solutions based on the single analog. They had created more than one solution for each design problem, but only one was based on the given analog. Thus, it was clear from this study that multiple solutions had not been created during the prior experiment.

Fig. 10. Participant Solutions for "Exercise Equipment Design Problem and Air Mattress Analogy"

Design Problem:

Design a kitchen utensil to sprinkle flour over a counter.

- **The only material that is available to build the kitchen utensil from is various thickness of stainless steel wire.**
- **The entire kitchen utensil must be made from only one thickness of wire.**
- **The kitchen utensil must be manufactured by bending and cutting the wire only.**
- **The kitchen utensil must be capable of containing the powdered substance and carrying the powdered substance 1 meter without losing the powdered substance.**

Create as many solutions as possible based on the analogy.

Analogy- This device serves a number of functions. The two sections hold the substances allowing them to be moved. A force separates the sections and the substance is released.

Solutions by different participants

Fig. 11. Participant Solutions for "Kitchen Utensil Design Problem and Toy Analogy"

Principles to Generate Multiple Solutions

Overview

A qualitative study was done to identify patterns and form principles/ guidelines to help designers to generate multiple solutions. The data was collected from various examples described in the motivation section in chapter 1and the reanalysis of prior analogy data.

Method

   1. *Procedure*

Initial research on innovations based on analogies showed that a Gecko's Foot helped develop two new products like a wall climbing robot and an adhesive. So, more research on this example showed that many more novel products like magnetic grips, tires, synthetic super glue, etc. had been developed based on this analog. This led to an important observation that one analog had led to the development of a variety of products in different domains. As this example was an analogy from nature, further research was carried out to search more examples in that field. This led to the finding of Lotus Effect analogy and Shark analogy. Again it was observed that these examples had inspired many innovative products. Thus, these examples were selected to study the possibility of generating multiple solutions from a single analog.

From the examples of a Gecko's Foot, Lotus Effect and Shark (Figures 2-5) patterns like geometry/shape, scaling, etc. were identified that helped generate multiple solutions. The reanalysis of the prior analogy data showed that participants had not generated multiple solutions for the given design problem based on the given analog as they were not instructed to do so, but this helped to identify the patterns in the features they had used to generate the solutions.

Results

Looking at the patterns from the examples, the list of features and solutions from the prior experiment, a set of principles was formulated for generating multiple solutions (Figure 12).

1. Design by listing features/characteristics of source analogy

List properties/characteristics of source analogy and draw inferences using them to get multiple solutions.

Inflate/Deflate

example   Airmattress

Perforated

Using substace available at the place

2. Design by Sizing/Scaling

Identify the scale of source analogy and then find out solutions at different or same scale.

Source	Target	Source	Target
Meso scale	Macro scale	Nano	Nano

3. Design by changing the problem

Manipulate or change the design problem according to the source analogy to get new solutions.

example   Given source analog as Gecko, limit/change the design problem to design a wall climbing device.

Fig. 12. List of Principles to Generate Multiple Solutions
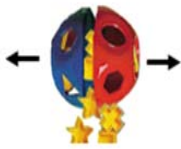
4. Principle/Counter Principle (or) Process/ Counter Process

Identify a principle of source analogy and then identify its counter principle and find solutions to a problem or generate new solutions based on this.

example	Source	Principle	Counter principle	Target
		Adhesion	Friction	Tires

5. Compare and Contrast

Take two analogies and comapre & contrast them. Based on this list generate new solutions.

example	Gecko & Spider	Compare	Contrast
		Climb	Different methods of climbing

6. Geometry

Given geometry of a source analogy, use this geometry to create solutions having same/similar geometry.

example	Source	Target
	Toy (sphere)	

7. Structural Alignment

8. Conceptual Combination

Fig. 12. Continued

CHAPTER IV

RESEARCH QUESTIONS AND HYPOTHESES

Based on the background, the following research questions are posed:

- Can engineers draw multiple solutions (multiple inferences) from a single analog? If so, what types of inferences are typically made from the analog? What inferences are more and less likely to occur? Are relational (functional) or surface features more likely to be mapped?

- What causes the high level principles of an analog more likely to be mapped while in the presence of noise products?

Based on the prior literature and to investigate these questions three hypotheses have been proposed.

Hypothesis 1: A lone designer is able to generate multiple inferences from a single source analog when instructed to do so.

This hypothesis is based on Holyoak's One-to-One Constraint in Analogical Mapping and Inference Theory (Krawczyk et al., 2005). The constraint theory restricts the mapping of one element from an analog in the base to multiple elements in the target. In Holyoak's study people occasionally generate multiple mappings but find it hard to generate multiple inferences. Based on the one-to-one constraint, it is possible to generate multiple inferences but cognitively difficult. People generally generate multiple inferences from multiple isomorphic mappings rather than a single homomorphic mapping. In the field of design there are a number of examples where more than one

inference was drawn from a single analog. The example of a Gecko's Foot shows that

multiple products have been developed and the ability to generate multiple inferences is

very useful. In order to see if the engineers can generate multiple mappings when

instructed to do so and how many they are able to generate, an experiment is conducted.

Hypothesis 2: The identification and mapping of the high level principle increases with multiple source analogs and decreases with the presence of extraneous products (noise products).

This hypothesis is based on previous studies (Namy & Gentner, 2002; Markman

& Gentner, 1993; Gick & Holyoak, 1983; Loewenstein et al., 1999) which observed that

providing two examples was better than one example. This observation was made over

different domains. There is little research that talks about the use of higher number of

examples and their benefits for a designer, or the ability of a designer to derive high

level principles in the presence of extraneous information.

Hypothesis 3: The effects of multiple analogs will depend on the number of extraneous products present. Statistically, the number of source analogs and the number of extraneous products will interact to predict the identification and mapping of the high level principle.

This is an extension of the second hypothesis. As hypothesis 2 states that the mapping of the high level principle is affected by the number of analogs and the amount of extraneous information, it is likely possible that the two factors will also interact.

Two experiments are conducted to evaluate the hypothesis and the results are analyzed.

CHAPTER V

EXPERIMENT 1- GENERATING MULTIPLE SOLUTIONS

Overview

A single condition, requiring one hour, was conducted to evaluate the proposed hypothesis that a lone designer can generate multiple inferences from a single source analog when instructed to do so. The participants were given a design problem and asked to generate multiple solutions based on the analog. Next, a feature listing task required participants to list the features they used from the analog to generate solutions. This task was conducted to identify patterns in the type and frequency of features used.

Method

Participants

The participants were graduate and undergraduate Mechanical Engineering students at Texas A&M University, seven graduates and one undergraduate. The undergraduate student was recruited from a Mechanical Engineering senior design class and the graduate students were recruited through posted flyers. All the participants received paid compensation.

Procedure

1. *Training*

The participants were taught what multiple solutions were by being shown examples of multiple solutions generated based on a single analog (Figure 13 and Figure 14). Participants received printed handouts which started with a definition of an analogy- "Analogy in engineering design is used as a tool to solve design problems. Use of an analogy to solve design problems gives innovative solutions." The next part explained the definition of multiple solutions, their use in engineering design with detailed examples and graphics. The definition was "Multiple solutions mean finding more than one solution from a given analogy by using various features from the analogy. Multiple solutions are very useful in the process of design as there would be more than one solution available for a design problem and hence designers' can select the best solution from the various options available". This was followed with a detailed explanation of the examples (Gecko's Foot-Figure 13 and Air Mattress-Figure 14) and the various solutions obtained from both these analogies. The Gecko's Foot example was developed from a literature review of innovations based on a gecko (Autumn et al., 2002; Campolo et al., 2003; Menon et al., 2004; Sitti & Fearing, 2003). The Air Mattress example was developed based on the participant solutions from a previous analogy study (Linsey, 2007). The entire training lasted ten minutes.
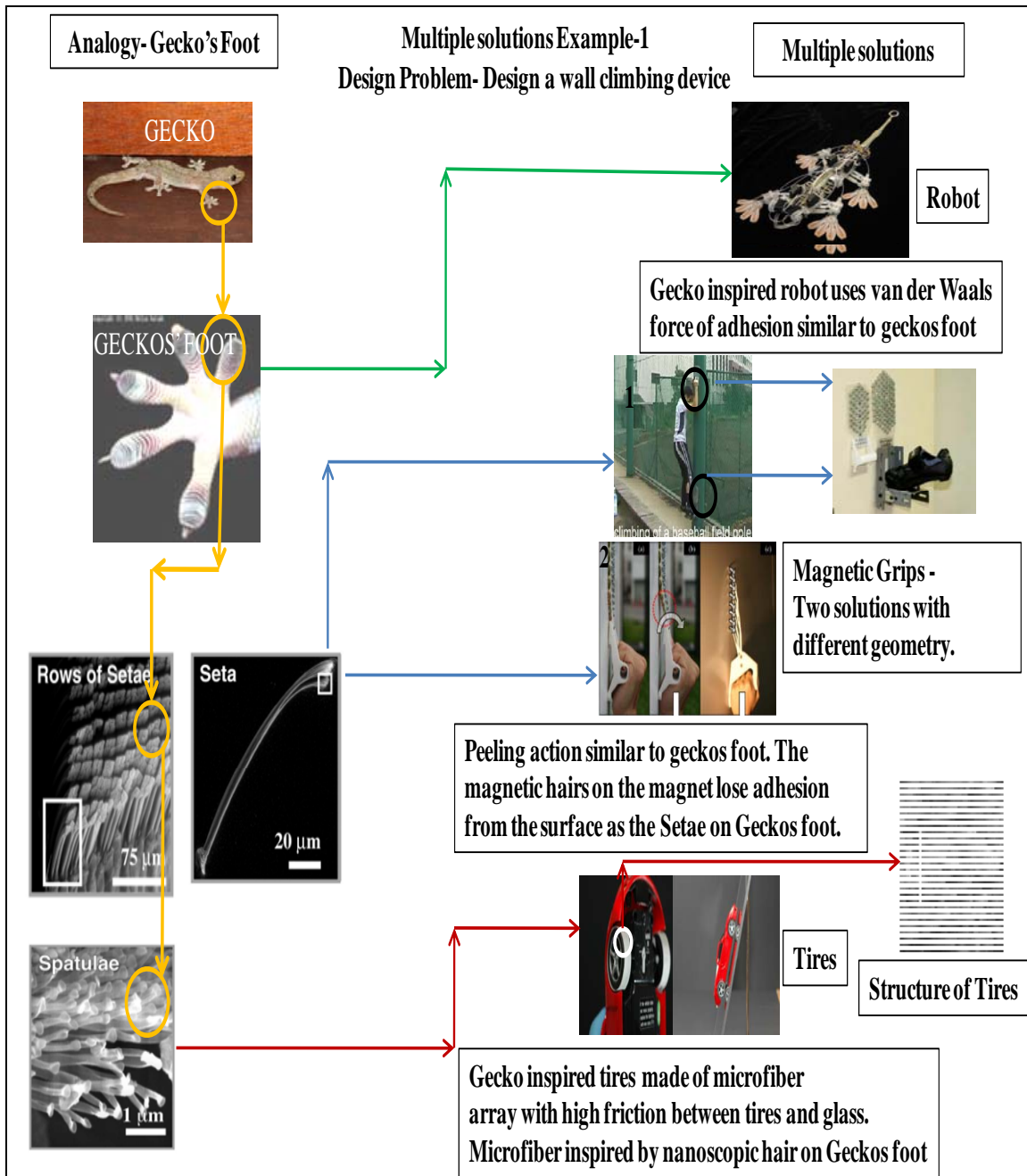
Fig. 13. Multiple Solutions Example from a Single Source Analog "Gecko's Foot"

Multiple solutions Example-2

Analogy- Air Mattress
Design Problem- Design exercise equipment that can be carried in a suitcase

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

Fig. 14. Multiple Solutions Example2 "Air Mattress"

2. *Idea Generation*

The training session was followed by an idea generation task. In this task, the participants were given an analog and design problem (Figure 15 and Figure 16). The design problem was used in a prior analogy experiment and the participants in that

experiment did not spontaneously generate multiple solutions (Linsey, 2007). The participants were then asked to generate multiple solutions based on the analog and to describe their ideas using sketches and/or words on 11" by 17" paper. The idea generation task lasted thirty minutes.   Multiple colors of pens were changed at five, ten and twenty minutes to record when ideas were generated. A five minute warning was given before the end of the activity.
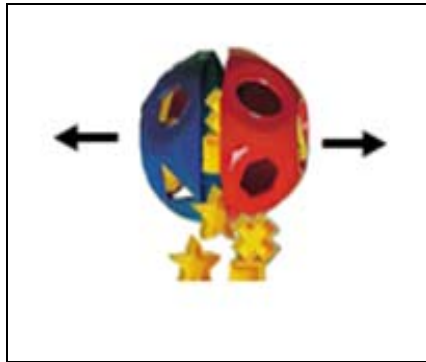
Fig. 15. Analog

Design Problem:

Design a kitchen utensil to sprinkle flour over a counter.

- **The only material that is available to build the kitchen utensil from is various thickness of stainless steel wire.**
- **The entire kitchen utensil must be made from only one thickness of wire.**
- **The kitchen utensil must be manufactured by bending and cutting the wire only.**
- **The kitchen utensil must be capable of containing the powdered substance and carrying the powdered substance 1 meter without losing the powdered substance.**

Create as many solutions as possible based on the analogy.

Fig. 16. Design Problem-Flour Sifter

3. Feature Listing

The next task was feature listing. In the feature listing task, the participants had to list features from the given analog which they used to generate their solutions. They were also required to identify these features on their solutions. Prior to beginning this task, the participants were given examples of features including geometry/shape, material, and physical principles such as Van der Waals force, friction, and adhesion. They were also given specific examples of features for the Air Mattress (Figure 14) such as inflate/deflate, easy storage and use of available substance. The purpose of this task was to identify the patterns in the features, i.e. the type of features (functional or surface) and the frequency of the features being used.

At the end of the experiment the participants were asked to fill out a survey and participate in a five minute interview. The survey measured demographic information and previous design experience.   In the interview the participants were asked few questions regarding the experiment. The main purpose of the interview was to check if all the instructions, material and tasks were clear. The entire experiment lasted for fifty minutes.

Metrics

The results from a previous analogy study showed that participants did not create multiple solutions when asked to generate ideas for the same design problem and analog as in this experiment. So the main aim of this experiment was to see whether multiple solutions could be created from a single analog and how easy it was for the participants

to do this. In order to evaluate this, the number of ideas each participant generated based on the source analog was measured.

The data from the feature listing task was evaluated to identify the patterns in the type and frequency of features used. Features like geometry, shape, etc. were classified as surface features and features like holding the substance, force required to open/close, etc. were classified as functional features (Table 6). Depending on what features the participants used, the solutions were divided as ones using surface features and ones using functional features. If the participants used the shape of the analog, e.g. sphere, to generate an idea, it was classified as a solution based on surface feature. If the participants used the functionality of the analog i.e. force required to separate the parts, hold/contain substance, it was considered as a solution based on functional features. Depending on the total number of surface and functional solutions generated the frequency of features used was determined.

An inter-rater agreement was also done to cross check the results of number of ideas generated based on the given analog and the frequency of features used. The participants' evaluation was correlated with the evaluation of the experimenter and a Pearson's correlation of 0.85 was observed for the number of ideas generated based on the given analog. A second rater other than the experimenter also analyzed the data and a Pearson's correlation was determined between the two raters. The second rater was a graduate student from engineering background, aware of the hypothesis of the experiment. The Pearson's correlation was observed to be 0.82 for the number of ideas based on the analog.

A percentage agreement was determined between the two raters for the frequency of features (surface or functional) used for generating solutions. A low value of 25% agreement (two matching data points out of eight) was observed for the frequency of functional features used and 62.5% for the frequency of surface features used.

Table 6. List of Surface and Functional Features for the Multiple Solutions Experiment

		SURFACE FEATURES
1		Geometry/Shape
2		Two halves/ Two parts
3		Holes on surface
		FUNCTIONAL FEATURES
1		Hold/ Contain Substance
2		Carry substance for a distance without letting it fall
3		Force to open/close
4		Pull apart and release the substance

Results and Discussion

Hypothesis: A lone designer is able to generate multiple inferences from a single source analog when instructed to do so.

The data from the eight participants was analyzed and showed the average number of multiple solutions generated was three (Figure 17). This is consistent with Holyoak's theory and shows that when instructed to do so participants can create

multiple solutions based on a single analog. Given the average was only three ideas in a

half hour; this is clearly a very difficult task for which engineers need support.
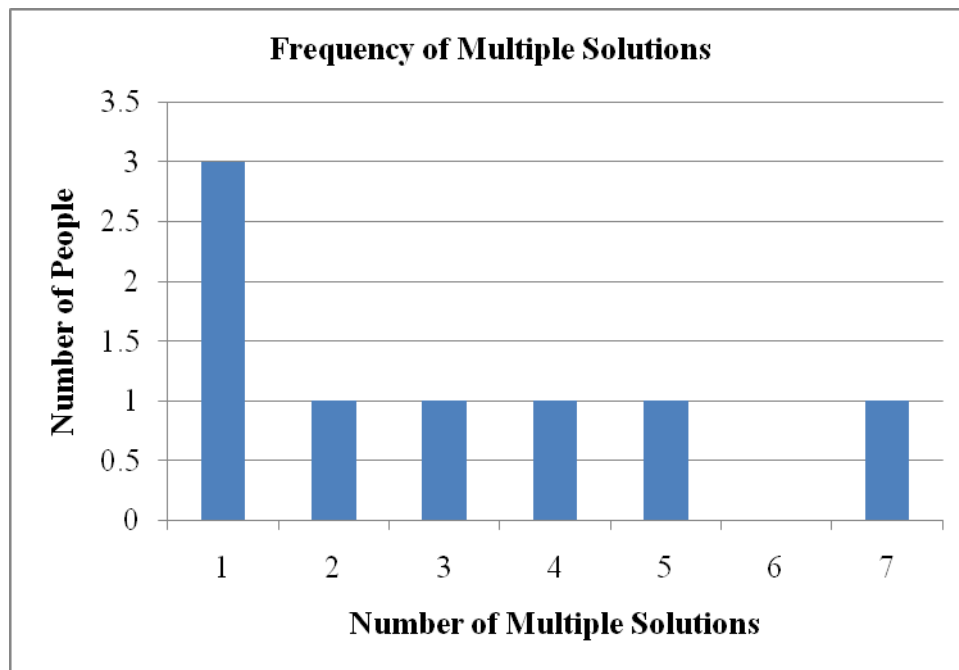
Fig. 17. Frequency of Multiple Solutions Generated by Participants

Feature Listing

The other information from this experiment was the pattern of features used for

generating ideas. It was observed that some participants had used just one feature from

the analog to generate solutions and some had used multiple features. The features listed

by participants and the number of ideas created using those features showed that there

was a greater use of functional features than surface features (Table 7). On an average

there were two ideas created based on functional features and one idea based on surface

features. The average number of ideas based on the functional features was more than that based on the surface features. This implied that the frequency of functional characteristics used was more than the surface characteristics to create multiple solutions. The functional features are used in greater frequency than surface features in this study but the sample size is too small for this to be statistically significant (Figure 18). Therefore, from the initial pilots a trend is observed in the type of features used for generating multiple solutions. This result supports the theory of one-to-one constraint which says that multiple inferences are created from multiple isomorphic mappings rather than a single homomorphic mapping. A larger sample size is required to make a statistically significant conclusion.
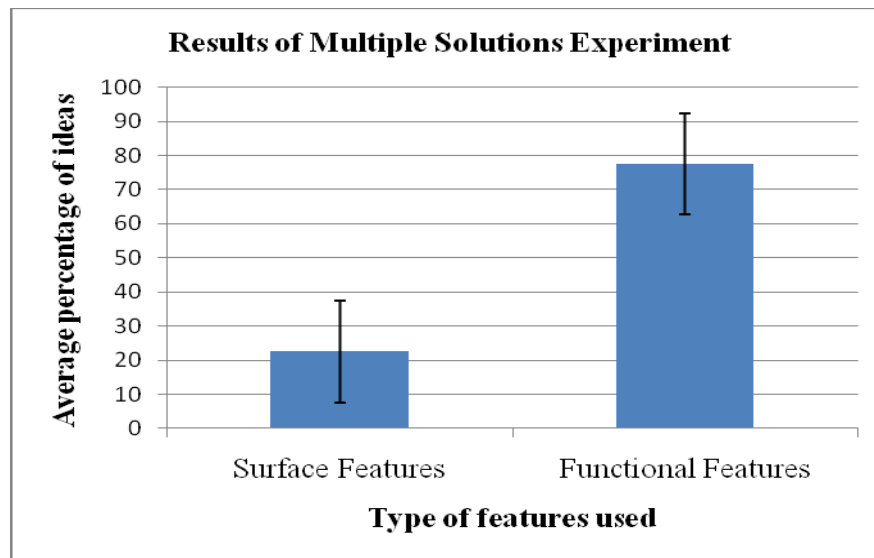
Fig. 18. Average Percentage of Ideas Based on Surface and Functional Features. Error Bars are +/- One Standard Error

Table 7. Summary of Results for the Multiple Solutions Experiment

Total number of ideas based on functional features	18
Average number of Multiple Solutions per participants based on functional features	2

Total number of ideas based on surface features	6
Average number of Multiple Solutions based on surface features	1

Implications of Multiple Solutions Experiment for Design

From the experiment it was observed that participants created multiple solutions for a design problem from a single analog when instructed to do so. Generally, participants tend not to create multiple solutions. They generate solutions, but not all are based on the analog. In this experiment, they generated multiple solutions, but it was a difficult task as they generated only three multiple solutions on an average in thirty minutes. This implied that when directed to or when asked for, designers can create more than one solution for a given problem based on a given analog, but it would be a difficult task. So, there is a need to provide guidance to designers for generating multiple solutions. This can be in the form of a set of detailed design principles similar to TRIZ/TIPS, or by providing examples like in this experiment. Design methods have to be developed to formulate principles based on prior studies and examples of analogies from various domains.

Generating multiple inferences based on a single analog would help designers create more solutions and an opportunity to compare different solutions. As the number

of solutions increases, the designer will have a wide choice of solutions to select from for the design problem. The analogical inferences can then be evaluated and the best one that solves the design problem can be chosen. Thus, multiple solutions provide a likely path for designers to evaluate and compare their solutions and select the best possible solution available.

CHAPTER VI

EXPERIMENT 2- LEARNING DESIGN PRINCIPLES FROM MULTIPLE

ANALOGS

Overview

To further explore the analogical reasoning process, a between-subjects factorial experiment evaluated the effects of multiple analogs (one or five) and amount of noise (none or 3 noise products per analog) on idea generation and the mapping of a high level design principle (energy storage through elastic material deformation). Participants were given a design problem, a set of products (Figure 19) and then asked to generate solutions.

 Method

Participants

The participants in this experiment were undergraduate and graduate Mechanical Engineering students from Texas A&M University. There were a total of thirty-four undergraduate students and thirteen graduate students; forty-seven total participants for the two hour study. There were forty-one male and six female participants with an average of eight months engineering work experience. Twelve graduate and thirty-four undergraduate students were recruited from their Mechanical Engineering design classes. One graduate student was recruited through posted flyers. Most of the participants received class credit as compensation. Two undergraduate and one graduate student received paid compensation.

Fig. 19. Analogs and Associated Extraneous Products

Materials

Participants were provided with a set of products and distracters according to conditions. They were also provided with pens and paper for sketching and a printed description of the design problem.

Design Problem

The participants were given a printout of the design problem (Figure 20) along

with a hand sketch as shown in Figure 21.

NASA astronauts are on a mission to Mars and a critical component has broken down; "Door Pin Lock" as shown in the handout. NASA engineers are anticipating this situation. They want to design features into the parts ahead of time allowing astronauts multiple avenues to provide temporary solutions to this problem.

NASA is looking for innovative solutions to fix this problem. So, your task is to provide a temporary fix to this problem satisfying the following condition.

- **The door pin must automatically return to the locked position even when there is no electricity.**

Since the parts are still being designed, you can add or remove features to the parts.

NASA will send supplies to the space station with the astronauts. The supplies will consist of a wide variety of materials and tools but NASA has not decided what materials and tools will be needed for this problem. It costs them millions of dollars per pound, so they want to send as little material as possible. So your solutions will help to determine what supplies to send.

Constraints:

- **You cannot use a metal coil spring. NASA is aware of this solution and needs others.**

Your task is to design a temporary mechanism to move the pin back to the locked position.

Generate as many solutions as possible for the given design problem.

Fig. 20. Design Problem for the Multiple Analogies Experiment
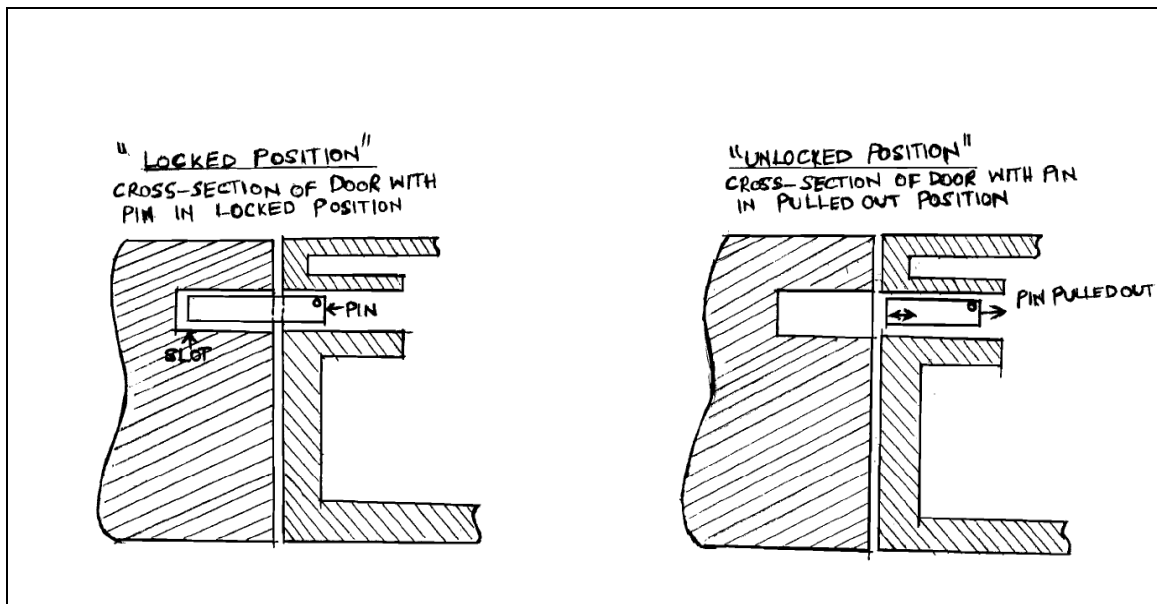
Fig. 21. Design Problem Sketch for Multiple Analogies Experiment

Procedure

The overall procedure was same for all the conditions. The products and distracters were described and demonstrated briefly before the idea generation task. The participants were given products and asked to generate ideas for the given design problem. They were instructed that the given products may or may not help to generate ideas. The participants were asked to sketch and/or use words to describe their ideas, and to generate one idea per sheet of paper. This was a forty minute activity. They were given a warning five minutes before the time. Different colors of pen were used during the activity with a change of pen at five, ten, twenty, and thirty minutes. The aim of pen change was to keep track of when the ideas were generated.

In the next task the participants were given an example of an analogy-"Burr & Velcro" and they were asked to cross out the ideas that did not use the given products as analogies. This was followed by a five minute feature listing task called "Feature Listing for All Products". It was the same as in the "Multiple Solutions" experiment. In this task the participants were asked to list all the features that they had used from the given products to generate each of the ideas. There was a five minute break after this task.

The next task after break was the product feature listing task called "Feature Listing for Implemented Products". The participants were given sheets with a picture of the products they had used to generate ideas and two columns for features not used and features used. They were asked to list all the features used and five features not used from the products during idea generation. This was a ten minute activity. The next task was similarity rating, which was divided into two parts, product similarity rating and feature similarity rating. In the product rating task the participants were asked to compare each of their ideas with the products and rate their similarity on a scale of 1 to 9, 1 indicating low similarity and 9 indicating high similarity. They were given printed sheets with boxes to rate the similarity. This was a five minutes task. The second part was to compare the features not used with the features used during idea generation and rate their similarity on the same scale. This was also a five minutes task. The total task was for ten minutes and its aim was to identify how similar the ideas were to the given product and identify patterns in the features used for idea generation.

The next two tasks were to identify the high level principle of the given products. In the first stage the participants were asked to identify the high level principle that many

of the given products shared in common and mark the ideas with a star that used that principle. This was a five minute task. In the second stage the participants were presented with the set of products that all shared the same high level principle which solved the design problem. They were given a sheet with a picture of the products and then asked to list the principle that the given set of products shared in common, circle any ideas already generated based on that principle and then generate more ideas for the design problem based on that principle. This was a ten minute task.

At the end of the experiment the participants were asked to fill out a survey and participate in a five minute interview asking questions about their demographic information and previous design experience. The purpose of the interview was to check if all the instructions and activities were clear and to remove bugs from the experiment. The entire experiment lasted for one hour and fifty minutes.

Metrics

In order to evaluate the hypothesis that the mapping of high level principle increases with an increase in the number of products and decreases with an increase of noise, identification of the high level principle was used as a main metric. The metric was whether the participants identified the high level principle or not and if yes at what stage. In the first stage the participants were asked to list the principle that many of the products shared in common and in the second stage they were told that the given set of products shared a high level principle and were asked to list it. Apart from the experimenter, a second rater (a graduate mechanical engineering student, aware of the

hypothesis) analyzed the data for the high level principle and a Cohen's Kappa of 0.74 was observed between the two raters.

Results and Discussion

Hypothesis: The mapping of the high level principle increases with an increase in the number of products and decreases with the amount of noise.

Results are shown for the first stage of principle identification for all conditions. As expected there was a clear increase in the mapping of the high level principle as the number of products was increased from one to five (Figure 22 and Figure 23). Also there was a significant decrease in the mapping of the high level principle when noise products were presented with the analogs. So, this shows that the noise products have a negative effect on the mapping of the high level principle.

From, Figure 22 there is a clear interaction between the number of products and number of distracter products. The bar chart in Figure 23 also indicates the increase in the percentage of high level principle listed with an increase in number of products from condition 1 (one product) to condition 2 (five products), decrease in the percentage of high level principle with an addition of distracters (conditions 3 and 4). The percentage of high level principle listed increases from 50% in condition 1 to 90 % in condition 2. It decreases to 50% in condition 3, 36% in condition 4.

The statistical results from the logistic regression test indicate these results are statistically significant. A logistic regression is used as an appropriate test because of the binary outcomes (the principle was identified or not). The logistic regression shows a

statistically significant effect of one predictor (i.e. analogs) on the identification of high level principle and no significant effect of the second predictor (i.e. noise information) (analogs- Wald= 6.085, p = 0.014, distracters- Wald= 1.941, p= 0.164), (Table 8). A quasi complete separation was observed in the statistical test due to a near 100% data point in one of the experimental conditions. So the interaction effect could not be considered and only the main effects were run. There is a clear indication from the plot in Figure 22 that there is an interaction effect between the two predictors. This implies that even the distracters have an effect on the identification of the high level principle being mapped.

Thus, the results from the regression test and the graphs in Figure 22 and Figure 23 show a significant effect of the number of products and distracters on the mapping of the high level principle.

Table 8. SPSS Output Table Showing Results from Binary Logistic Regression

	Wald	Significance (p)
Product	6.085	0.014
Distractor	1.941	0.164
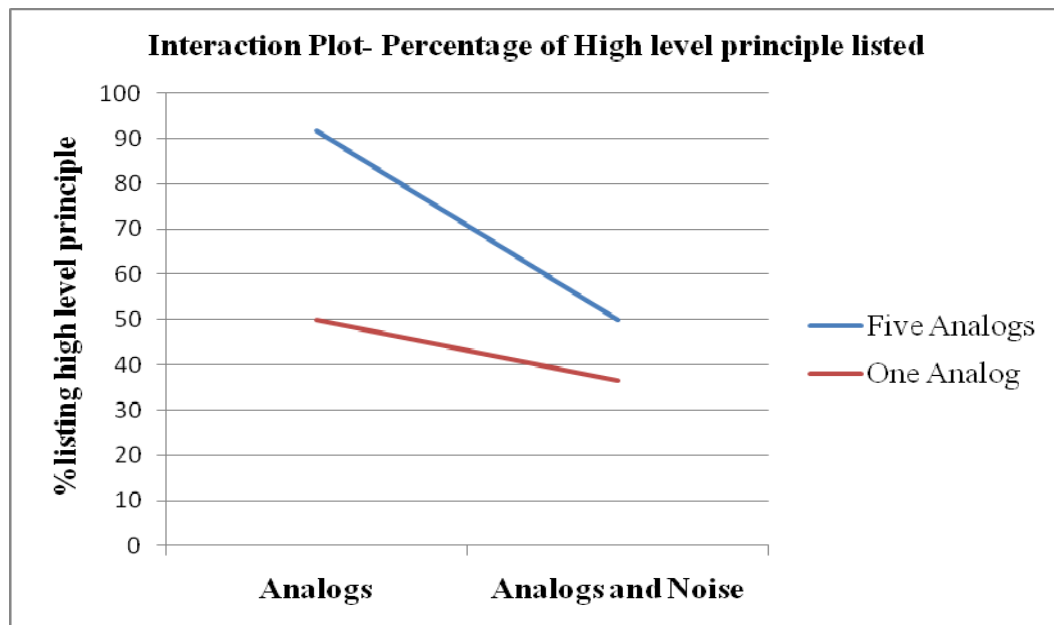
Fig. 22. Interaction Plot Showing Percentage of High Level Principle Listed in Each of the Four

Experimental Conditions
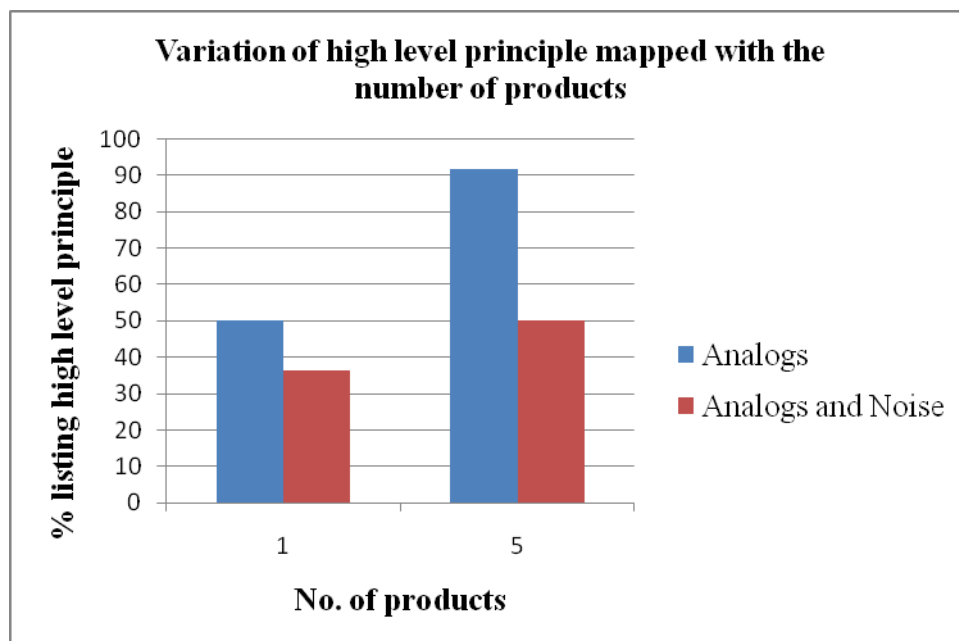
Fig. 23. Variation of the Percentage of High Level Principle Listed with the Number of Products

Implications of Multiple Analogies Experiment for Design

The "Multiple Analogies" experiment showed that there is an effect of noise on designers' ability to generate ideas and identify the high level principle from multiple analogs. The study showed that presence of noise decreases the chances of identifying the high level principle of the analog while generating ideas for a design problem. It was observed that with five analogs and low noise students identified the principle 90% of the time. This implied that students were good at deriving principles when multiple examples were provided with low noise. As the percentage of deriving principles was so high, it implied that further study needs to be done with less than five examples and explore their effect. So, it is preferred to have less noise or distraction while deriving principles of design and generating ideas for a design problem using analogs. This is only possible in a controlled experiment, in a research setting where the amount of noise can be controlled so that the designer can identify the high level principles from the analogs. This method of minimizing noise is possible in an educational field by giving examples to teach students to work with less noise. This is not possible in the real world as disturbance is always present. So, there is a need to develop design methods to support designers to help them derive the high level principles of design. The design methods could be some form of guidelines/examples that would teach/train the designers to work with less noise in the real world and focus on deriving principles of design from analogs.

CHAPTER VII

CONCLUSIONS AND FUTURE WORK

"Multiple Solutions" Conclusions

Multiple paths are available to improve the design-by-analogy process. Designers often use analogies to generate novel ideas for a design problem. An analogy provides multiple directions for generating solutions, but it is generally difficult to generate multiple inferences from a single analog. Multiple inferences provide the opportunity to explore multiple solutions, identify the optimal solution and evaluate the analogical inferences.

The results from Experiment 1- "Generating Multiple Solutions" indicate that it is possible to generate more than one solution from a single source analog when directed to do so. It was observed that only three ideas were generated on an average in thirty minutes, which is rather low. Clearly, generating multiple solutions is a difficult task. This observation is contrary to previous analogy studies. Unless directed to, participants do not generally generate multiple solutions (Linsey et al., 2008; Linsey, 2007). They generate multiples solutions, but only one will be based on a presented analog.

As the number of multiple solutions generated is low even after providing examples and training, a design method needs to be developed to help designers improve this process further. Multiple inferences would help designers create more solutions for the design problem. Multiple solutions would also likely assist them with evaluating their inferences and in selecting the best possible solution available.

The other preliminary finding from the "Multiple Solutions" experiment was that more functional features were mapped from the analog than surface features. This result was not statistically significant.   This was an important finding contrary to prior studies which showed that generally surface features are used more than functional features to generate ideas (Namy & Gentner, 2002; Gentner, 1983).

"Multiple Solutions" Future Work

A bigger sample size and more work needs to be done on the "Multiple Solutions" experiment to make a strong conclusion. From the results of experiment 1, it is clear that a further study is required on the "Multiple Solutions" experiment with a bigger sample size of at least 20.This is to have enough data points to reduce the standard error and make a statistically significant conclusion of the results from the pilot studies and to find out whether or not multiple solutions can be created from a single source analog. Also due to very low values of agreement on the frequency of features used, more data and a coding scheme is needed to evaluate the results about the frequency of features.

Another area of future research would be to develop a design method like a detailed set of principles/guidelines to form multiple solutions by looking at more examples from different domains. A small set of guidelines was identified as part of this thesis, but was not tested. So, there is a need to develop a method that would assist designers to create multiple solutions and evaluate their inferences.

As further research on drawing multiple inferences from a single source analog, it will be interesting to develop a database (collection) for analogies from different domains which would generate multiple solutions. For example, a database having a collection of analogies from nature like a Gecko, Lotus Effect, Honeycomb or other domains that can generate multiple solutions for design problems. This database can be combined with computer programs and many solutions can be generated for a given design problem. Also with the development of such a database, one can explore if the analogies and solutions can be combined to give better options to solve the problem. This would help designers have more variety of solutions and they could compare and select the best available one.

It will also be helpful to improve the sketching ability of engineers and develop methods to evaluate the sketches. Engineers are not very good at drawing and it is very hard to interpret their sketches and generally sketches lead to ambiguous results. So, it will be useful to teach (like training for certain period of time) or include sketching as part of course work for engineers to improve their sketching skill.

"Multiple Analogies" Conclusions

Designers also frequently derive principles of design from sets of analogs, but this a difficult task in real world atmosphere where noise is inherent. The "Multiple Analogies" experiment explores this phase of design where designers have difficulty identifying the high level principle from a set of analogs while generating ideas for a design problem.

The results from the second experiment showed that the presence of noise with the analogs affects the identification of the high level principle. It was observed that with five examples and low level of noise, participants identified the high level principle 90% of the time and with high amount of noise (15 noise products), the percentage of identifying the principle dropped. This implies that mapping of the principle increases with the increase in the number of analogs and presence of noise reduces this percentage. Thus, noise distracts the designers and reduces their ability to derive the high level principles from the analogs while generating ideas for design problems.

"Multiple Analogies" Future Work

Future work will focus on developing approaches and methods to assist designers in identifying high level principles of design. Further exploration of multiple analogies is needed and additional experiments will be run for more conditions (Table 9). The "Multiple Analogies" experiment was a pilot for a larger 3X4 factorial experiment (products=1, 2, 3, 5 and distracter ratio=0, 1, 3). As an initial experiment, only four of the twelve conditions were run. The table below shows the different conditions of the experiment (Table 9).

The data from the follow up activities of feature listing and similarity rating needs to be analyzed. The aim of the two feature listing tasks was to identify the patterns in the features, along with the frequency of features used and not used to generate ideas. The data for these tasks has to be coded and analyzed to check if the participants used more surface features or functional features from the analogs.

Table 9. Different Conditions of the Multiple Analogies Experiment

Number of examples

		1	2	3	5
Number of Distracters	0	Condition 1			Condition 2
	1				
	3	Condition 4			Condition 3

An approach similar to the one used in "Multiple Solutions" experiment can be used. The purpose of the similarity rating tasks (i.e. product rating and feature rating) was to check to what extent the participants believed their ideas were similar to the given analogs. The product rating was to check how similar the generated idea was to the given product and the feature rating was to check the similarity between features used and features not used during idea generation. The product rating analysis will show to what extent the ideas are similar to the products.

As further research, a design method needs to be developed to support designers deriving high level principles of design. This may include providing multiple examples, developing guidelines and teaching/training designers to work in the presence of noise.

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APPENDIX A

EXPERIMENT 1 – GENERATING MULTIPLE SOLUTIONS

PARTICIPANT MATERIALS

1. *Training*

"Analogy" in engineering design is used as a tool to solve design problems. Using an analogy to solve design problems gives innovative solutions. For example, if we take analogies from nature like a "Gecko's foot" and "Burr" many innovative solutions have been obtained. A wall climbing robot, Magnetic Grips and Tires have been developed based on an analogy to a Gecko's foot and Velcro has been developed based on an analogy to Burr. So, Analogy aids in creating innovative solutions. It's also possible to find more than one solution from a single analogy. This is called Multiple Solutions. Multiple Solutions mean finding more than one solution from a given analogy by using various features from the analogy. Multiple Solutions are very useful in the process of design as there would be more than one solution available for a design problem and hence designers can select the best solution from the various options available. This study is looking at developing Multiple Solutions in engineering design.

| Burr | Velcro |

69

Multiple solutions

Robot

Gecko inspired robot uses van der Waals force of adhesion similar to geckos foot

Magnetic Grips - Two solutions with different geometry.

Structure of Tires

Multiple solutions Example-1
Design Problem- Design a wall climbing device

Tires

Peeling action similar to geckos foot. The magnetic hairs on the magnet lose adhesion from the surface as the Setae on Geckos foot.

1

2

Gecko inspired tires made of microfiber array with high friction between tires and glass. Microfiber inspired by nanoscopic hair on Geckos foot

Analogy- Gecko's Foot

GECKO

GECKOS' FOOT

Seta

20 µm

Rows of Setae

75 µm

Spatulae

1 µm

Multiple solutions Example-2

Analogy- Air Mattress

Design Problem- Design exercise equipment that can be carried in a suitcase

Constraints:

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

PUNCHING BAG FILL WITH WATER

INFLATED PUNCHING BAG

DEFLATE TO FIT

BOXING GLOVES

WEIGHT

PUNCHING BAG FILLED WITH WATER

AIR MATTRESS FOR HOUSE GUESTS

INFLATABLE YOGA MAT

FILL WITH WATER

WATER DUMBBELLS

PUNCHING BAG ANALOGOUS TO INFLATABLE PUNCHING BAG FILLED WITH SAND

PUNCHING BAG FILLED WITH SAND

NOZZLE

BODY SUIT THAT CAN BE FILLED WITH WATER,

BODY SUIT

2. *Analogy and Design problem*

Analogy:
This device serves a number of functions. The two sections hold the substances allowing them to be moved. A force separates the sections and the substance is released.

Design Problem:

Design a kitchen utensil to sprinkle flour over a counter.

- The only material that is available to build the kitchen utensil from is various thickness of stainless steel wire.

- The entire kitchen utensil must be made from only one thickness of wire.

- The kitchen utensil must be manufactured by bending and cutting the wire only.

- The kitchen utensil must be capable of containing the powdered substance and carrying the powdered substance 1 meter without losing the powdered substance.

3. *Survey*

Survey Questions

Question	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
A more detailed explanation is needed for what multiple solutions are.					
The Gecko example was helpful to understand multiple solutions.					
The Air Mattress example was helpful to understand multiple solutions.					

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

3rd

4th

5th or more

6) Country where your undergraduate university is located _____

7) Do you have engineering industrial experience (Not class projects or a Research assistantship), working **full-time** (including internships, co-ops)?

    a. Yes.

    b. No.

        _____ Months   _____ Years

8) Do you have engineering industrial experience (Not class projects or Research Assistantship), working **part-time**?

    a. Yes.

    b. No.

        _____ Hrs/Week   _____ Months _____ Years

9) Had you heard about this experiment 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.

10) Had you heard about 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.

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

EXPERIMENT SCRIPT

Check List
Items required for the experiment

☐ Participant consent forms (2 copies)

☐ Handout of example

☐ Handout with analogy and problem description

☐ Sheet for recording questions and answers

☐ Sheets for sketching (11*17)

☐ Sticky Notes

☐ Stop watch utensils

☐ Time Recording Sheet

☐ Multiple colored writing(black, green, red ,blue, brown(sk))

☐ Extra paper

☐ Survey

☐ Interview sheet

☐ Stapler

☐ Payment vouchers

<u>*Consent*</u>
- Keep two copies of consent forms on table

- Black pen

- Keep training sheets on top right corner of the table.

As soon as each participant arrives: **Hello!!** "**You can put your backpack close to the wall and please turn off or silence your cell phones and please remove your watch.** Show them the work place. **"Please take your seat. We are ready to begin."**

Read the following statement:

"**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 for given design problem, to participate in a five minute interview and to complete a five minute survey at the end of the experiment. The study will require approximately 1 hour. Please let me know if you have any questions about the study."

Allow participants to read the form, at least three minutes. Answer all questions the participants ask. Wait until all participants have finished reading before proceeding. Then say, **"Do you have any questions?** (Answer) **If you agree to participate please sign the consent form and keep a copy for your records.**"

"I have one request before we begin: Please do not discuss the experiment with anybody in the Engineering Departments at TAMU until after May 31, 2010. The reason is that it will bias the results if a participant knows what the design problem is or what the tasks are."

Sign the consent forms and take them. If wished, sign copies for records.

Training (showing example of multiple inference)
Example of Multiple solutions

In this experiment you'll be creating multiple solutions from a single analogy. I'll give you a few examples about where multiple solutions have been generated based on a single analogy. A printout is available on the table on top right corner. Please turn over the handouts and follow along. Please remember that I'll take away the handouts once we are done with this section and you'll not have any of this material for the next task. Glance briefly over the graphics and please follow along carefully as I read.

"Analogy" in engineering design is used as a tool to solve design problems. Using an analogy to solve design problems gives innovative solutions. For example, if we take analogies from nature like a "Gecko's foot" and "Burr" many innovative solutions have been obtained. A wall climbing robot, Magnetic Grips and Tires have been developed based on an analogy to a Gecko's foot and Velcro has been developed based on an analogy to Burr. So, Analogy aids in creating innovative solutions. It's also possible to find more than one solution from a single analogy. This is called Multiple Solutions. Multiple Solutions mean finding more than one solution from a given analogy by using various features from the analogy. Multiple Solutions are very useful in the process of design as there would be more than one solution available for a design problem and hence designers can select the best solution from

the various options available. This study is looking at developing Multiple Solutions in engineering design.

In example-1 in the handout, A "Gecko's foot" is the analogy and the design problem is to "design a wall climbing device."

The left hand side of the graphic shows a complete Gecko, below which is an enlarged image of a Gecko's Foot. This is followed by the image of the microstructure of the Gecko's toe. Each toe consists of rows of fine hair like structures called "Setae". Individual hair is called "Seta". The last image shows the structure of nanoscopic heads called "Spatula" present on top of each of the "Seta". The right hand side of the graphic shows the multiple solutions obtained from the given analogy. Different solutions are obtained from this analogy taking into account different features of the analogy.

The "Robot" is a solution based on the Gecko's foot. It foot shape is similar to a Gecko's foot and like a Gecko's foot uses van der Waals force of adhesion to climb and stick to the wall, the Robot also uses similar van der Waals force to move up the wall.

"Magnetic Grips" is another solution obtained from the given analogy and is used for wall climbing. It has a "Peeling action" similar to a Gecko's foot. In the graphic there are two images representing a magnetic solution for the design problem but they have different geometry. The magnetic hairs on the magnet lose contact from the surface as the Seta on Geckos foot. This action starts at the bottom of the magnet and then progresses upward just like the Seta.

The last image shows Gecko inspired "Tires". These Tires have fibers similar to the Spatula on the Gecko's foot which account for the high friction between the Tires and the glass surface.

So, if we consider the wall climbing device design problem and the analogy of a Gecko's foot, there is more than one solution based on this single analogy. The Robot, Magnetic Grips and Tires are devices for wall climbing, but they use different features from a Gecko's foot.

Similarly, in example-2 the analogy is "Air mattress for house guests" and the problem is to "design exercise equipment that can be carried in a suitcase."

The graphic shows various solutions based on the single analogy of an Air mattress for this design problem.

In the graphic beginning from top of the Air mattress and looking in the clock wise direction, the "Punching bag" is filled with water and it inflates/deflates like the Air mattress. The next solution is an "Inflatable Yoga mat" which also uses inflate/deflate feature. The "Water Dumbbell" is a collapsible weight that is filled with water when exercising and emptied and stored when not in use. The other unique solution is a "Body suit" which can be filled with water and used for exercising. The last solution is a "Punching bag" again, but this time it uses sand instead of water.

Again, for the given design problem, more than one solution exists.

Are there any questions?

Answer questions if any. (Record the questions and answers)

Take those sheets back and give design problem and idea gen sheets.

Design Problem

Today, your task is to generate solutions for a given design problem. Generate as many solutions as possible. You will be given an analogy to generate solutions. Create as many solutions as possible for the presented design problem based on the analogy like the examples shown in the first section. I will read out the description of the analogy and the design problem for which you will generate solutions. A printout is available below the stack of paper on the table on the top left corner. Please turn it over and follow along as I read it.

The analogy for the design problem is as shown in the handout on the table. This device serves a number of functions. The two sections hold the substances allowing them to be moved. A force separates the sections and the substance is released.
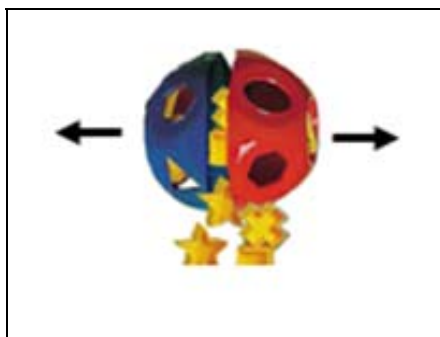
The design problem is as follows.

Design a kitchen utensil to sprinkle flour over a counter.

- **The only material that is available to build the kitchen utensil from is various thickness of stainless steel wire.**

- **The entire kitchen utensil must be made from only one thickness of wire.**

- **The kitchen utensil must be manufactured by bending and cutting the wire only.**

- **The kitchen utensil must be capable of containing the powdered substance and carrying the powdered substance 1 meter without losing the powdered substance.**

   Create as many solutions as possible based on the analogy.

Sketch and use words to describe your ideas. Please sketch as many ideas as you can per sheet of paper. You will have 30 minutes for this activity. I'll give you a warning 5 min before the time is up. We'll be using different colours of pen to keep track of when the ideas are generated. I'll exchange your pen at regular intervals of time.

Remember to generate as many solutions as possible based on the analogy.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

After 5 min say **"I'll exchange your pen now."** Then change pen (from black to red)

After next 5 min change pen (from red to green)

After next 10 min change pen (from green to blue)

Give warning 5 min before- **"You have 5 min left for this activity"**

Your time is up now.

Please number the ideas and put an X next to the ones that don't use the analogy.

Let me know when you are done.

Once they are done, take back the pen.

Feature listing task

Give Brown pen, Air mattress example handout and Sticky notes to the participants.

Your next task is to list the features from the analogy that you used to generate each idea. For each idea list the features below/next to the idea. The following are a few examples of features.

Geometry/Shape, function, material, physical principles like friction, Van der Waals force, energy, etc.

Now consider the specific example of an air mattress in front of you. Various solutions are obtained based on this analogy taking into account its different features. Beginning from the top, the punching bag filled with water uses the inflate/deflate feature like the air mattress. Similarly, the yoga mat is filled with air and it also uses the inflate/deflate feature. The Water dumbbell is a collapsible weight. It is filled with water and emptied and stored when not in use. Again it uses inflate/deflate feature and easy storage feature from the air mattress. The body suit filled with water and the punching bag filled with sand also use the inflate/deflate feature. So, looking at these solutions and features we can state the high level

principle as "use of substance available at a place where the device is to be used to make it functional".

Now "please list all the features from the analogy that you used for generating each idea. Also label these features on the sketches. Please keep the sheets as a stack and then start listing the features. If there is not enough space on the sheet to list features, use the sticky notes and paste it next to the sketch."

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

Please let me know when you are done. You may begin now.

Start the stop watch

Once they are done stop the watch and Collect the sheets

Survey
Give blue pen. **Please fill out the survey.**
Collect the survey.

Interview (Pilots only)

"Now I'll ask you some questions about your experience. This interview will take about 5 minutes."

1. What do you think about the experiment?
2. How did you generate concepts? Did you find solutions based on the analogy?
a.   Which features did you use or what principles did you take from the given analogy?
b. If no, what did you use?
3. How helpful were the given examples of Gecko's foot and air mattress to understand multiple solutions? Which one of them was better?
4. How useful was the given analogy to solve the design problem?
6. Was the design problem clearly stated?

Disbursement

"Thank you very much for your participation in the experiment.

CASH: <u>Hand out payment slips, $10.</u> **"Please fill in your name and UIN. In order to receive the cash, please see Michelle Mitchell in the ME office, as stated on the voucher. Do you have any questions?"**

EXTRA CREDIT: Write name and class affiliation down. Do not write date or experiment number down. **"OK, you'll receive the extra credit. Do you have any questions?**

"Then, thank you again for your participation. Please do not talk about the experiment to anybody in Mechanical until after May 31, 2010, as it will bias the results. Have a good afternoon/ evening.

First, Last Name	Class Affiliation

RULES TO EVALUATE MULTIPLE SOLUTIONS

Features of the analogy:

Surface features:

1. Geometry/ shape

2. Two halves/2 parts

3. Holes

Functional Features:

1. Hold/Contain substance

2. Carry substance for a distance without letting it fall

3. Force to open/close or pull apart and release the substance

Rules to classify Multiple Solutions

Please sort the sheets in the order given (1 to 8) and rate each idea in those sheets.

1. Check if the generated solution is based on the given analogy

    a. Check if any surface features are used in the solution

    b. Check if any functional features are used in the solution

2. If either surface or functional features or both features are used, classify the

    solution as based on the analogy

3. If none of the features are used, then the solution is not based on the analogy

4. Rating the solutions

    a. Solution based on surface features- 1

    b. Solution based on functional features- 2

c. Solution using both surface and functional features- 3

d. Solution not based on the analogy- 0

RESULTS FROM THE MULTIPLE SOLUTIONS EXPERIMENT

Participant no	No. of ideas based on surface features	No. of ideas based on functional features	Total number of ideas based on analogy	Average percentage of ideas per participant using functional features	Average percentage of ideas per participant using functional features
1	0	1	1	100	0
2	2	0	2	0	100
3	0	3	3	100	0
4	4	1	5	20	80
5	0	4	4	100	0
6	0	7	7	100	0
7	0	1	1	100	0
8	0	1	1	100	0
Average	**0.75**	**2.25**		77.5	22.5
Standard deviation	**1.488047618**	**2.314550249**		42.00340122	42.00340122
Standard error	**0.526104281**	**0.818317088**		14.85044492	14.85044492

SAMPLE SOLUTIONS

III & IV

Force fitted cap to open and put in flour

Sides with holes — is widened in them for flour to pass out

Exit/Entry for flour

- Function

- Shape (The Hemispherical portion on top ensures tight fit. due to friction.)

The above diagram can be thought of as 2 separate independent vessels

1) The Bottom surface has no hole. Entry & Exit is done by opening the top

2) Bottom surface has hole from where flour exits. It enters by opening the

---

II

Entry for flour
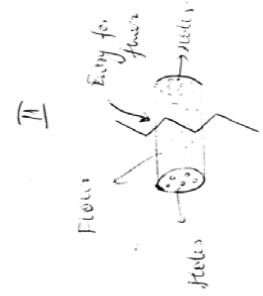
Flour

Holes

A very thick wire can be bent to form a cylinder which is fitted along the line

Flour is kept inside

The ends are cut middles with holes for flour to come out

The ends are closed by bending essential thick wires

- Function (2 sections are made like you example idea. Tilting either ways provide an outlet.

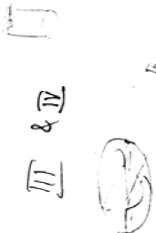- Material (I used a very thick wire hollow tube. There was no need of bending)

Hole

Flour

Container II has a depression where flour can be kept.

Container I has hole on the free side from where flour is sprinkled out.

The 2 containers are force fitted

- Function (2 sections which can be separated only using a force.

one stores flour

Another provides an outlet

flour is put inside by forcing open the containers)

FEATURES USED

FEATURES USED

FEATURES USED

APPENDIX B

EXPERIMENT 2 – LEARNING DESIGN PRINCIPLES FROM MULTIPLE ANALOGIES

PARTICIPANT MATERIALS

1. Design Problem

NASA astronauts are on a mission to Mars and a critical component has broken down; "Door Pin Lock" as shown in the handout. NASA engineers are anticipating this situation. They want to design features into the parts ahead of time allowing astronauts multiple avenues to provide temporary solutions to this problem.

NASA is looking for innovative solutions to fix this problem. So, your task is to provide a temporary fix to this problem satisfying the following condition.

- The door pin must automatically return to the locked position even when there is no electricity.

Since the parts are still being designed, you can add or remove features to the parts.

NASA will send supplies to the space station with the astronauts. The supplies will consist of a wide variety of materials and tools but NASA has not decided what materials and tools will be needed for this problem. It costs them millions of dollars per pound, so they want to send as little material as possible. So your solutions will help to determine what supplies to send.

Constraints:

- You cannot use a metal coil spring. NASA is aware of this solution and needs others.

Your task is to design a temporary mechanism to move the pin back to the locked position.

Generate as many solutions as possible for the given design problem.

2. *Design Problem sketch*
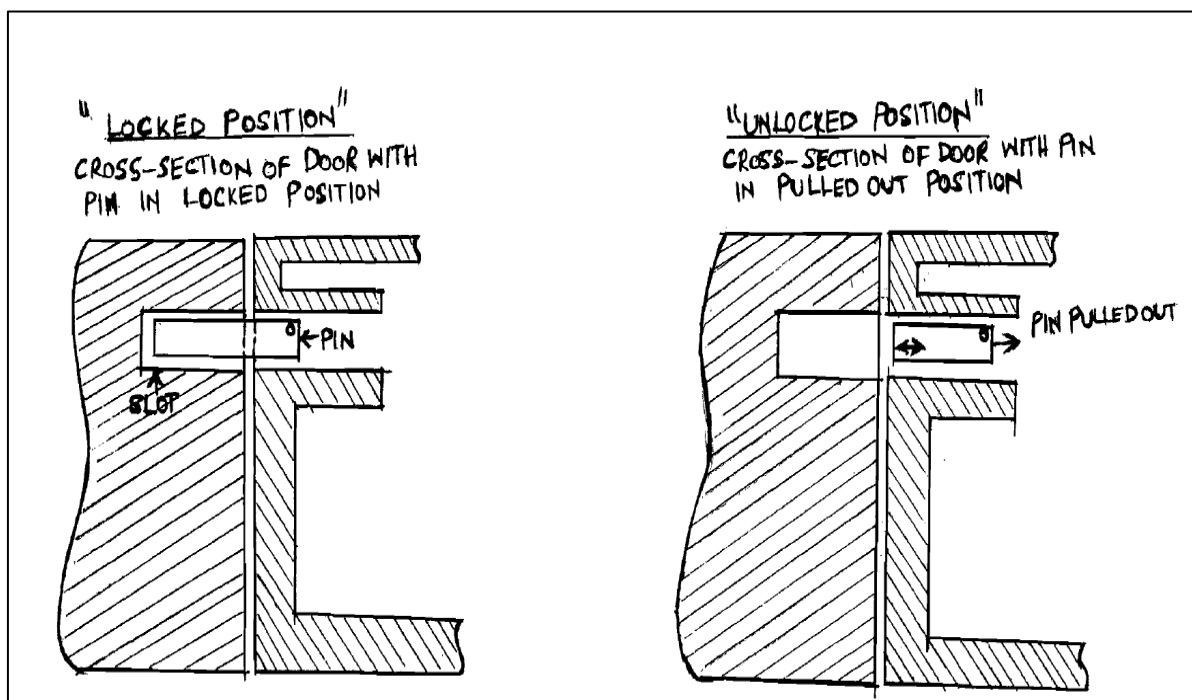
3. Analogy example- Burr and Velcro
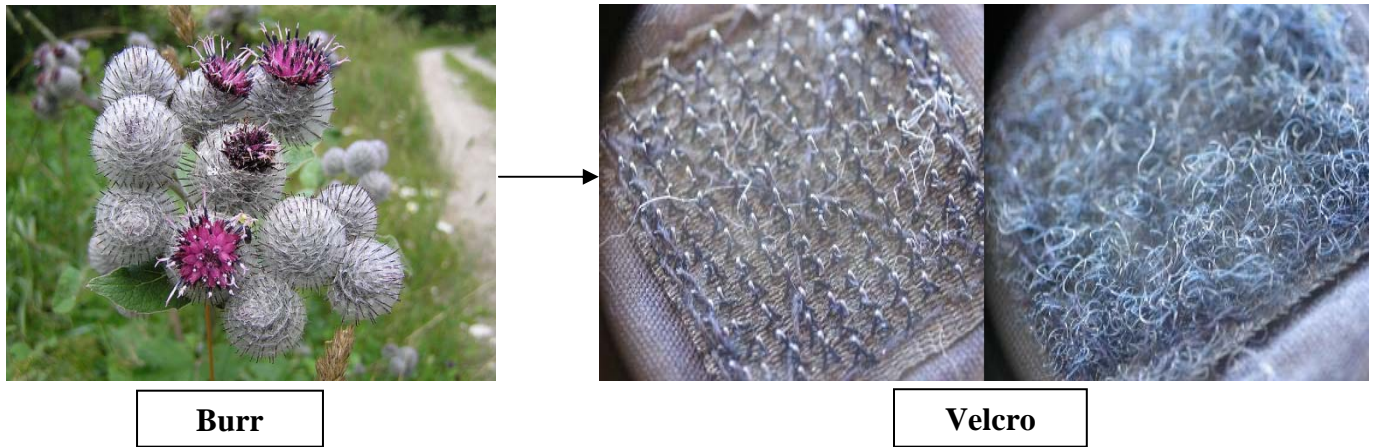
| Burr | Velcro |

4. Air mattress example for "Feature listing for all products" task
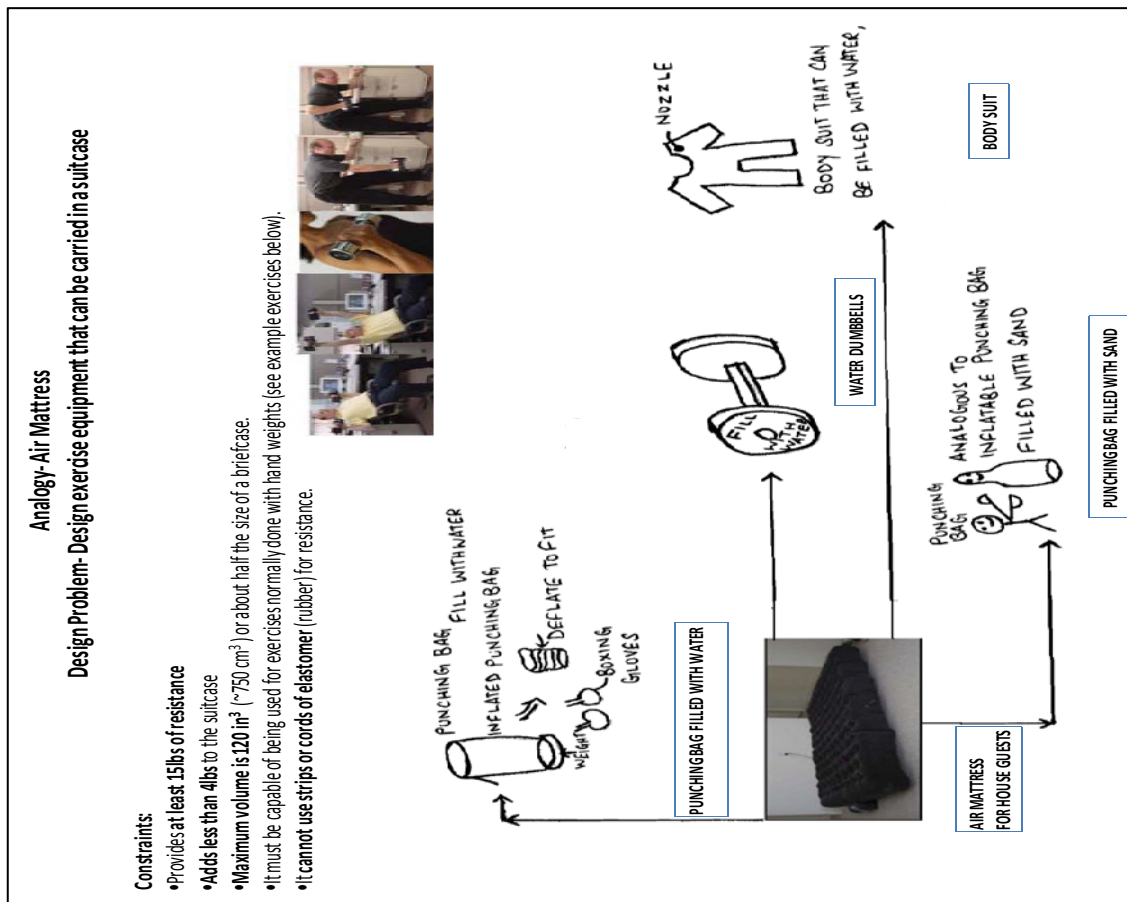
5. Products for different conditions

Product for condition 1
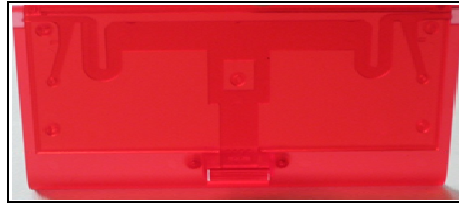
Sticky note holder lid

Products for condition 2

Product name
Flour Duster
Constant Force Spring
Sticky Note Holder Lid
Bungee Blast
Compression Spring

Products for condition 3

Flour Sifter	Spiral Chip Holder	Tomato Slicer	Compression Spring
Flour Duster	Sticky Note Flip Book	Bungee Blast	Pool Noodle
Egg Yolk Separator	Sticky Note Holder Lid	Desk organizer	Burner Coil
Constant Force Spring	Business Card Holder	Immersion Heater	Model Rocket
Paper Airplane	Tea Strainer	Pen Stand	Whisk

Products for condition 4

	Product name	
	Sticky Note Flip Book	
	Sticky Note Holder Lid	
	Business Card Holder	
	Desk organizer	

6. "Feature listing for implemented products" task

The participants received the product feature listing sheets according to the condition they were in. The conditions and the products given are described in the scripts. The sheets are the same for all products.

Flour Duster

Features <u>not</u> used	Features used
A.	1.
B.	2.
C.	3.
D.	4.
E.	5.
	6.
	7.
	8.
	9.
	10.

Compression Spring

Features **not** used	Features used
A.	1.
B.	2.
C.	3.
D.	4.
E.	5.
	6.
	7.
	8.
	9.
	10.

Sticky Note Holder

Features <u>not</u> used	Features used
A.	1.
B.	2.
C.	3.
D.	4.
E.	5.
	6.
	7.
	8.
	9.
	10.

Bungee Blast

Features <u>not</u> used	Features used
A.	1.
B.	2.
C.	3.
D.	4.
E.	5.
	6.
	7.
	8.
	9.
	10.

Constant Force Spring

Features <u>not</u> used	Features used
A.	1.
B.	2.
C.	3.
D.	4.
E.	5.
	6.
	7.
	8.
	9.
	10.

7. Product similarity rating

The participants received the sheets shown below with the idea number and names of products according to the condition of the experiment. All the sheets looked the same except for that all conditions did not have all the products listed.

Scale: 1= Low similarity -   9= High similarity

Your Idea no	Name of Product	Similarity Rating	Your Idea no	Name of Product	Similarity Rating	Your Idea no	Name of Product	Similarity Rating
1	Flour Sifter		2	Flour Sifter		3	Flour Sifter	
1	Flour Duster		2	Flour Duster		3	Flour Duster	
1	Egg Yolk Separator		2	Egg Yolk Separator		3	Egg Yolk Separator	
1	Constant Force Spring		2	Constant Force Spring		3	Constant Force Spring	
1	Paper Airplane		2	Paper Airplane		3	Paper Airplane	
1	Spiral Chip Holder		2	Spiral Chip Holder		3	Spiral Chip Holder	
1	Sticky Note Flip Book		2	Sticky Note Flip Book		3	Sticky Note Flip Book	
1	Sticky Note Holder Lid		2	Sticky Note Holder Lid		3	Sticky Note Holder Lid	
1	Business Card Holder		2	Business Card Holder		3	Business Card Holder	
1	Tea Strainer		2	Tea Strainer		3	Tea Strainer	
1	Tomato Slicer		2	Tomato Slicer		3	Tomato Slicer	
1	Bungee Blast		2	Bungee Blast		3	Bungee Blast	
1	Desk Organizer		2	Desk Organizer		3	Desk Organizer	
1	Immersion Heater		2	Immersion Heater		3	Immersion Heater	
1	Pen Stand		2	Pen Stand		3	Pen Stand	
1	Compression Spring		2	Compression Spring		3	Compression Spring	
1	Pool Noodle		2	Pool Noodle		3	Pool Noodle	
1	Burner Coil		2	Burner Coil		3	Burner Coil	

8. Feature similarity rating

The participants received the sheets as shown below according to the condition and the products they had used during the experiment. All the sheets looked the same for all products.

Scale: 1= Low similarity   -   9= High similarity

Sticky Note Holder

Feature **not** used	Feature used	Similarity Rating	Feature **not** used	Feature used	Similarity Rating	Feature **not** used	Feature used	Similarity Rating
A	1		B	1		C	1	
A	2		B	2		C	2	
A	3		B	3		C	3	
A	4		B	4		C	4	
A	5		B	5		C	5	
A	6		B	6		C	6	
A	7		B	7		C	7	
A	8		B	8		C	8	
A	9		B	9		C	9	
A	10		B	10		C	10	

9. Listing high level principle stage 1

The participants were given a sheet with the following statement on it. This was same for all conditions.

<u>List the one principle that many of the products share in common, which solves the</u> <u>design problem</u>

10. Listing high level principle stage 2

The participants received a sheet with the pictures of products on it depending on the condition they were in. For condition 1and 4- sticky note holder lid, for conditions 2 and 3- the products shown below.

List the principle that the given set of products share in common, which solves the design problem.

11. Survey

Survey Questions

Question	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
I used the given products to generate solutions.					
The given products were useful to create solutions.					
I found the similarity rating task hard.					

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

3rd

4th

5th or more

6. Country where your undergraduate university is located _____

7. Do you have engineering industrial experience (Not class projects or a Research assistantship), working **full-time** (including internships, co-ops)?

    a. Yes.

    b. No.

_____ Months   _____Years

8. Do you have engineering industrial experience (Not class projects or Research Assistantship), working **part-time**?

    a. Yes.

    b. No.

_____ Hrs/Week   _____Months _____ Years

9. Had you heard about this experiment 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.

10. Had you heard about 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.

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

EXPERIMENT SCRIPT

CONDITION 1

Check List

☐ Participant consent forms (2 copies)

☐ Stop watch utensils

☐ Time Recording Sheet

☐ Product (to be given)

☐ Design problem description

☐ Paper for sketching(including hand sketch)

☐ Multiple colored writing(black, red, green, blue, brown, maroon, violet, Strawberry

(sk), Red (sk), pink (sk), light blue pen, orange pen)

☐ Sheets for product feature listing task (features not used & used)

☐ Sheets for similarity rating task

☐ Sheets for list of principle and idea gen (given only products)

☐ Extra paper

☐ Survey

☐ Interview sheet

☐ Stapler

☐ Payment vouchers

Consent

- Keep two copies of consent forms on table

- Black pen

- Keep design problem, blank paper and paper with sketch for idea generation on top right corner and product on the top left corner of the table

As soon as each participant arrives: **Hello!!** "**You can put your backpack close to the wall and please turn off or silence your cell phones.** Show them the work place. **"Please take your seat. We are ready to begin."**

Read the following statement:

"**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 for given design problem, to participate in a five minute interview and to complete a five minute survey at the end of the experiment. The study will require approximately two hours. Please let me know if you have any questions about the study."

Allow participants to read the form, at least three minutes. Answer all questions the participants ask. Wait until all participants have finished reading before proceeding.

Then say, **"Do you have any questions?** (Answer) **If you agree to participate please sign the consent form and keep a copy for your records.**"

"I have one request before we begin: Please do not discuss the experiment with anybody in the Engineering Departments at TAMU until after May 31, 2010. The

reason is that it will bias the results if a participant knows what the design problem
is or what the tasks are."

Sign the consent forms and take them. If wished, sign copies for records.

Design Problem - Door Pin Lock

**Your task is to generate as many solutions as possible for the given design problem.
You have a product in front of you that may or may not help you to generate
solutions. I'll briefly describe and demonstrate the product.**

Show them the product and then describe and demonstrate.

1. **Sticky note holder Lid- This is the lid of a sticky note holder. It consists of a
   latch. When the latch is moved down, the sticky note holder opens. This is the
   actual product and it works like this.**

**Now, I will read out the description of the design problem for which you will
generate solutions. A printout is available below the stack of paper on top right
corner of the table. Please flip the stack over and follow along as I read.**

**NASA astronauts are on a mission to Mars and a critical component has broken
down; "Door Pin Lock" as shown in the handout. NASA engineers are anticipating
this situation. They want to design features into the parts ahead of time allowing
astronauts multiple avenues to provide temporary solutions to this problem.
NASA is looking for innovative solutions to fix this problem. So, your task is to
provide a temporary fix to this problem satisfying the following condition.**

- **The door pin must automatically return to the locked position even when there is no electricity.**

Since the parts are still being designed, you can add or remove features to the parts. NASA will send supplies to the space station with the astronauts. The supplies will consist of a wide variety of materials and tools but NASA has not decided what materials and tools will be needed for this problem. It costs them millions of dollars per pound, so they want to send as little material as possible. So your solutions will help to determine what supplies to send.

Constraints:

- **You cannot use a metal coil spring. NASA is aware of this solution and needs others.**

Your task is to design a temporary mechanism to move the pin back to the locked position.

Generate as many solutions as possible for the given design problem.

Remember that the product in front may or may not help you to generate solutions. Sketch and use words to describe your ideas. There are sheets with the design problem sketch on it. So, please sketch one idea per sheet of paper. If not you can also use the blank paper for sketching your ideas. Also write down everything even if it does not satisfy the constraint. Generate as many solutions as possible. You will have 40 minutes for this activity. I'll give you a warning 5 min before the time is up. We'll be using different colours of pen to keep track of when the ideas are

generated. I'll exchange your pen at regular intervals of time. Remember you can add or remove features into the parts to allow for temporary solutions.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

After 5 min say **"5 min are over. I'll exchange your pen now."**

After the 1ˢᵗ 5 min change pen- give red pen.

After next 5 min change pen- give green pen

After next 10 min change pen- give blue pen

After next 10 min change pen- give maroon pen

Time for next 10 min.

Your time is up now.

Now I'll give you an example of analogy which will be helpful for doing the next task. Consider the example of Burr and Velcro as shown in the handout. The design of Velcro is based on an analogy to Burr. Two strips of Velcro fasten together just like the spines on a burr.

Your next task is to number the ideas and put an X next to the ones that don't use the given product as analogy.

Let me know when you are done.

Once they are done, take back the pen.

**List of features mapped (Feature listing for all products)**
Give brown pen for this task.

Your next task is to list all the features you used from the given product to generate each of the ideas. The following are a few examples of features.

Geometry/Shape, function, material, physical principles like friction, adhesion, van der Waals force, energy, etc.

Now consider the specific example of an air mattress in front of you. Various solutions are obtained based on this analogy taking into account its different features. Beginning from the top, the punching bag filled with water uses the inflate/deflate feature like the air mattress. The Water dumbbell is a collapsible weight. It is filled with water and emptied and stored when not in use. Again it uses inflate/deflate feature and easy storage feature from the air mattress. The body suit filled with water and the punching bag filled with sand also use the inflate/deflate feature. So, looking at these solutions and features we can state the high level principle as "use of substance available at a place where the device is to be used to make it functional".

"Please list the features taken from the example product below/next to each idea and also label the features on the sketches." You'll have 5 minutes for this activity. Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch.

Once they are done stop the watch.

Break

You will now have a 5 min break. The restrooms are right there (point in direction)**, and a water fountain is around the corner from them. Please be back on time."**

<u>Product Feature Listing Task (For implemented products)</u>
Keep product, Violet pen, idea generation sheets and sheets for feature listing on the table.

"For the product on the right side of the table list all features you used from that product to generate each of the ideas. Also list five features that you did not use from the product. Please list/describe features in words or sketches. Also label the features on the given picture of the product.

The given sheets have a name and picture of the product and two columns for features not used and features used. Please describe in words or sketches the features not used and features used in the respective columns on the given sheets.

You'll have 10 minutes for this activity.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

Time the activity.

Once they are done, stop the watch.

Similarity Rating Task

Give back the sheets of paper from the idea generation (list of features mapped) task to

the participants. Give the sheet with product names and pictures. Give the sheet for

similarity rating and Strawberry (sk).

> **Your task is to compare each of the ideas you generated with the product**
>
> **and rate their similarity on a scale of 1-9, 1 indicating low similarity and 9**
>
> **indicating high similarity.**
>
> **Please compare the ideas and the product and rate their similarity in the**
>
> **respective columns on the given sheet and please leave the other unused**
>
> **boxes empty. You'll have 5 minutes for this task.**

Are there any questions before we begin?

Answer questions if any.

You may begin now.

Start the stop watch

Once they are done, stop the watch.

Give another similarity rating sheet, product feature listing sheets, idea gen sheets and

red (sk)

Your next task is to do a similarity rating on a scale of 1-9, between the list of

features not used during idea generation and the features used, 1 indicating low

similarity and 9 indicating high similarity.

Please compare the features not used with the features used and rate their

similarity in the respective columns on the given sheet and please leave the unused

boxes empty. For example you have to compare "A-1, A-2, so on…and then B-1, B-2 so on." You'll have 5 minutes for this task.

Are there any questions before we begin?

Answer questions if any.

You may begin now.

Start the stop watch

Once they are done, stop the watch.

1. Give sheets for high level principle listing task, design problem, idea generation and light blue pen. Give only the analogy and ask to relist the principle- **"Now you are given a printout with a picture the product. This product has a high level principle that can be used to solve the "door pin lock" problem given earlier in the experiment. Please list the principle of the given product on the page in front of you and then generate ideas for the design problem based on this principle. Please circle any solutions you have already generated based on this principle." The design problem is the same as before-** Give handout of design problem.

Again, sketch and use words to describe your ideas. Please sketch one idea per sheet. You will have 10 minutes for circling already generated ideas and for generating new ideas. I'll give you a warning 5 min before the time is up.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

After 5 min change pen- give orange pen

 Time for next 5 min

Stop the watch.

Your time is up now.

Collect the sheets.

Survey
Give blue pen. **Please fill out the survey.**

Collect the survey.

Interview (Pilots only)
 "I'll ask you now some questions about your experience. This interview will take

about 5 minutes."

1. What do you think about the experiment?
2. What is your opinion about the similarity rating task?
3. Was the design problem clearly stated?

<u>Disbursement</u>

"Thank you very much for your participation in the experiment.

CASH: <u>Hand out payment slips, $20.</u> **"Please fill in your name and UIN. In order to receive the cash, please see Michelle Mitchell in the ME office, as stated on the voucher. Do you have any questions?"**

EXTRA CREDIT: Write name and class affiliation down. Do not write date or experiment number down. **"OK, you'll receive the extra credit. Do you have any questions?**

"Then, thank you again for your participation. Please do not talk about the experiment to anybody in Mechanical until after May 31, 2010, as it will bias the results. Have a good afternoon/ evening."

First, Last Name	Class Affiliation

EXPERIMENT SCRIPT

CONDITION 2

Check List

☐ Participant consent forms (2 copies)

☐ Stop watch utensils

☐ Time Recording Sheet

☐ Products (to be given)

☐ Design problem description

☐ Paper for sketching(including hand sketch)

☐ Multiple colored writing(black, red, green, blue, brown, maroon, violet, Strawberry

(sk), Red (sk), pink (sk), light blue pen, orange pen)

☐ Sheets for product feature listing task (features not used & used)

☐ Sheets for similarity rating task

☐ Sheets for list of principle and idea gen (given only products)

☐ Extra paper

☐ Survey

☐ Interview sheet

☐ Stapler

☐ Payment vouchers

<u>*Consent*</u>

- Keep two copies of consent forms on table

- Black pen

- Keep design problem, blank paper and paper with sketch for idea generation on top right corner and products on the top left corner of the table

As soon as each participant arrives: **Hello!!** "**You can put your backpack close to the wall and please turn off or silence your cell phones.** Show them the work place. **"Please take your seat. We are ready to begin."**

Read the following statement:

"**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 for given design problem, to participate in a five minute interview and to complete a five minute survey at the end of the experiment. The study will require approximately two hours. Please let me know if you have any questions about the study."

Allow participants to read the form, at least three minutes. Answer all questions the participants ask. Wait until all participants have finished reading before proceeding. Then say, **"Do you have any questions?** (Answer) **If you agree to participate please sign the consent form and keep a copy for your records.**"

"I have one request before we begin: Please do not discuss the experiment with anybody in the Engineering Departments at TAMU until after May 31, 2010. The

reason is that it will bias the results if a participant knows what the design problem is or what the tasks are.”

Sign the consent forms and take them. If wished, sign copies for records.

Design Problem: Door Pin Lock

Your task is to generate as many solutions as possible for the given design problem. You have some products in front of you that may or may not help you to generate solutions. I'll briefly describe and demonstrate all the products.

Show them the product and then describe and demonstrate.

1. **Mini Flour Duster- This is a mini flour duster. The wire coils are separated by pressing the handle. It's placed in the flour in this position. When the handle is released, it contains flour between the wire coils in this position. It can then be used to dust the flour on a surface by pressing the handle slowly.**

2. **Bungee Blast- This is a Bungee blast toy. It works by pulling the rubber band with a finger, holding the tube with other hand and then releasing it.**

3. **Sticky note holder Lid- This is the lid of a sticky note holder. It consists of a latch. When the latch is moved down, the sticky note holder opens. This is the actual product and it works like this.**

4. **Constant force spring- This is a constant force spring.**

5. **Compression Spring- This is a metal compression spring.**

Now, I will read out the description of the design problem for which you will generate solutions. A printout is available below the stack of paper on top right corner of the table. Please flip the stack over and follow along as I read.

NASA astronauts are on a mission to Mars and a critical component has broken down; "Door Pin Lock" as shown in the handout. NASA engineers are anticipating this situation. They want to design features into the parts ahead of time allowing astronauts multiple avenues to provide temporary solutions to this problem. NASA is looking for innovative solutions to fix this problem. So, your task is to provide a temporary fix to this problem satisfying the following condition.

- The door pin must automatically return to the locked position even when there is no electricity.

Since the parts are still being designed, you can add or remove features to the parts. NASA will send supplies to the space station with the astronauts. The supplies will consist of a wide variety of materials and tools but NASA has not decided what materials and tools will be needed for this problem. It costs them millions of dollars per pound, so they want to send as little material as possible. So your solutions will help to determine what supplies to send.

Constraints:

- You cannot use a metal coil spring. NASA is aware of this solution and needs others.

Your task is to design a temporary mechanism to move the pin back to the locked position.

Generate as many solutions as possible for the given design problem.

Remember that the products in front may or may not help you to generate solutions. Sketch and use words to describe your ideas. There are sheets with the design problem sketch on it. So, please sketch one idea per sheet of paper. If not you can also use the blank paper for sketching your ideas. Also write down everything even if it does not satisfy the constraint. Generate as many solutions as possible. You will have 40 minutes for this activity. I'll give you a warning 5 min before the time is up. We'll be using different colours of pen to keep track of when the ideas are generated. I'll exchange your pen at regular intervals of time.

Remember you can add or remove features into the parts to allow for temporary solutions.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

After 5 min say **"5 min are over. I'll exchange your pen now."**

After the 1ˢᵗ 5 min change pen- give red pen.

After next 5 min change pen- give green pen

After next 10 min change pen- give blue pen

After next 10 min change pen- give maroon pen

Time for next 10 min.

Your time is up now.

Now I'll give you an example of analogy which will be helpful for doing the nest task. Consider the example of Burr and Velcro as shown in the handout. The design of Velcro is based on an analogy to Burr. Two strips of Velcro fasten together just like the spines on a burr.

Your next task is to number the ideas and put an X next to the ones that don't use any of the given products as analogies.

Let me know when you are done.

Once they are done, take back the pen.

List of features mapped (Feature listing for all products)

Give brown pen for this task.

Your next task is to list all the features you used from the given products to generate each of the ideas. Also name the product used next to the feature. The following are a few examples of features.

Geometry/Shape, function, material, physical principles like friction, adhesion, van der Waals force, energy, etc.

Now consider the specific example of an air mattress in front of you. Various solutions are obtained based on this analogy taking into account its different features. Beginning from the top, the punching bag filled with water uses the inflate/deflate feature like the air mattress. The Water dumbbell is a collapsible weight. It is filled with water and emptied and stored when not in use. Again it uses

inflate/deflate feature and easy storage feature from the air mattress. The body suit filled with water and the punching bag filled with sand also use the inflate/deflate feature. So, looking at these solutions and features we can state the high level principle as "use of substance available at a place where the device is to be used to make it functional".

"Please list the features taken from the example products below/next to each idea, name the product used next to the feature and also label the features on the sketches." You'll have 5 minutes for this activity.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch.

Once they are done stop the watch.

Product separation

From the set of products in front of you, please separate out the products that you used for generating ideas and keep them on the right side of the table.

Break

You will now have a 5 min break. The restrooms are right there (point in direction), and a water fountain is around the corner from them. Please be back on time."

__Products Feature Listing Task (For implemented products)__

Keep products (that they used for idea gen) separate and other products as earlier, Violet pen, idea generation sheets and sheets for feature listing (corresponding to the products used for idea gen) on the table

"For the products on the right side of the table list all features you used from that product to generate each of the ideas. Also list five features that you did not use from the product. Please list/describe features in words or sketches. Also label the features on the given picture of the product.

The given sheets have a name and picture of the product and two columns for features not used and features used. Please describe in words or sketches the features not used and features used in the respective columns on the given sheets.

You'll have 10 minutes for this activity.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

 You may begin now.

Start the stop watch

Time the activity.

Once they are done, stop the watch.

__Similarity Rating Task__

Give back the sheets of paper from the idea generation (list of features mapped) task to the participants.   Give the sheet with product numbers and names. Give the sheet for similarity rating and Strawberry (sk).

Your task is to compare each of the ideas you generated with each product and rate their similarity on a scale of 1-9, 1 indicating low similarity and 9 indicating high similarity.

Please compare the ideas and products and rate their similarity in the respective columns on the given sheet and please leave the other unused boxes empty. You'll have 5 minutes for this task.

Are there any questions before we begin?

Answer questions if any.

You may begin now.

Start the stop watch

Once they are done, stop the watch.

Give another similarity rating sheet, product feature listing sheets, idea gen sheets and red (sk)

Your next task is to do a similarity rating on a scale of 1-9, between the list of features not used during idea generation and the features used, 1 indicating low similarity and 9 indicating high similarity.

Please compare the features not used with the features used and rate their similarity in the respective columns on the given sheet and please leave the unused boxes empty. For example you have to compare "A-1, A-2, so on…and then B-1, B-2 so on." You'll have 5 minutes for this task.

Are there any questions before we begin?

Answer questions if any.

You may begin now.

Start the stop watch

Once they are done, stop the watch.

> **1.** Give sheets for high level principle listing task, design problem, idea
>
> generation and light blue pen. Give only the analogies and ask to relist the
>
> principle- **"Now you are given a printout with pictures of the products. All**
>
> **these products share the same high level principle that can be used to solve**
>
> **the "door pin lock" problem given earlier in the experiment. Please list the**
>
> **principle that the given set of products share in common on the page in front**
>
> **of you and then generate ideas for the design problem based on this**
>
> **principle. Please circle any solutions you have already generated based on**
>
> **this principle." The design problem is the same as before-** Give handout of
>
> design problem.

Again, sketch and use words to describe your ideas. Please sketch one idea per

sheet. You will have 10 minutes for circling already generated ideas and for

generating new ideas. I'll give you a warning 5 min before the time is up.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

After 5 min change pen- give orange pen

 Time for next 5 min

Stop the watch.

Your time is up now.

Collect the sheets.

Survey

Give blue pen. **Please fill out the survey.**

Collect the survey.

Interview (Pilots only)

 "I'll ask you now some questions about your experience. This interview will take about 5 minutes."

1. What do you think about the experiment?
2. What is your opinion about the similarity rating task?
3. Was the design problem clearly stated?

<u>Disbursement</u>

"Thank you very much for your participation in the experiment.

CASH: <u>Hand out payment slips, $20.</u> **"Please fill in your name and UIN. In order to receive the cash, please see Michelle Mitchell in the ME office, as stated on the voucher. Do you have any questions?"**

EXTRA CREDIT: Write name and class affiliation down. Do not write date or experiment number down. **"OK, you'll receive the extra credit. Do you have any questions?**

"Then, thank you again for your participation. Please do not talk about the experiment to anybody in Mechanical until after May 31, 2010, as it will bias the results. Have a good afternoon/ evening."

First, Last Name	Class Affiliation

EXPERIMENT SCRIPT

CONDITION 3

Check List

☐ Participant consent forms (2 copies)

☐ Stop watch utensils

☐ Time Recording Sheet

☐ Products (to be given)

☐ Design problem description

☐ Paper for sketching(including hand sketch)

☐ Multiple colored writing(black, red, green, blue, brown, maroon, violet, Strawberry

(sk), Red (sk), pink (sk), light blue pen, orange pen)

☐ Sheets for product feature listing task (features not used & used)

☐ Sheets for similarity rating task

☐ Sheet for writing high level principle

☐ Sheets for list of principle and idea gen (given only products)

☐ Extra paper

☐ Survey

☐ Interview sheet

☐ Stapler

☐ Payment vouchers

<u>*Consent*</u>

- Keep two copies of consent forms on table

- Black pen

- Keep design problem, blank paper and paper with sketch for idea generation on top right corner and products on the top left corner of the table

As soon as each participant arrives: **Hello!!** "**You can put your backpack close to the wall and please turn off or silence your cell phones.** Show them the work place. **"Please take your seat. We are ready to begin."**

Read the following statement:

"**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 for given design problem, to participate in a five minute interview and to complete a five minute survey at the end of the experiment. The study will require approximately two hours. Please let me know if you have any questions about the study."

Allow participants to read the form, at least three minutes. Answer all questions the participants ask. Wait until all participants have finished reading before proceeding. Then say, **"Do you have any questions?** (Answer) **If you agree to participate please sign the consent form and keep a copy for your records.**"

"I have one request before we begin: Please do not discuss the experiment with anybody in the Engineering Departments at TAMU until after May 31, 2010. The

reason is that it will bias the results if a participant knows what the design problem is or what the tasks are."

Sign the consent forms and take them. If wished, sign copies for records.

Design Problem: Door Pin Lock

Your task is to generate as many solutions as possible for the given design problem. You have some products in front of you that may or may not help you to generate solutions. I'll briefly describe and demonstrate all the products.

Show them the product and then describe and demonstrate.

1. **Flour Sifter- This is a Flour Sifter. The flour is sifted through the mesh by rotating the handle.**

2. **Tea strainer- This is a tea strainer**

3. **Immersion heater- This is a heating coil. It's used to heat water.**

4. **Whisk- This is a whisk. It's used to beat eggs.**

5. **Egg Yolk separator- This is a yolk separator. It separates the yolk from the egg white.**

6. **Mini Flour Duster- This is a mini flour duster. The wire coils are separated by pressing the handle. It's placed in the flour in this position. When the handle is released, it contains flour between the wire coils in this position. It can then be used to dust the flour on a surface by pressing the handle slowly.**

7. **Burner coil- This is an electric burner coil from a cooking range.**

8. **Pen stand- This is a pen holder made of stainless steel.**

9. **Bungee Blast-** This is a Bungee blast toy. It works by pulling the rubber band with a finger, holding the tube with other hand and then releasing it.

10. **Sticky note holder Lid-** This is the lid of a sticky note holder. It consists of a latch. When the latch is moved down, the sticky note holder opens. This is the actual product and it works like this.

11. **Tomato Slicer-** This is a slicer to slice tomatoes. The tomato is held between the two halves and sliced using a knife.

12. **Sticky note flip book-** This is a sticky note flip book.

13. **Desk Organizer-** This is a desktop organizer. It has slots to hold paper and other stationery.

14. **Constant force spring-** This is a constant force spring.

15. **Spiral chip holder-** This is a spiral chip holder used in restaurants.

16. **Model Rocket-** This is a Model rocket.

17. **Compression Spring-** This is a metal compression spring.

18. **Business card holder-** This is a business card holder.

19. **Pool Noodle-** This is pool noodle for floating in a pool

20. **Paper airplane-** This is a paper airplane.

Now, I will read out the description of the design problem for which you will generate solutions. A printout is available below the stack of paper on top right corner of the table. Please flip the stack over and follow along as I read.

NASA astronauts are on a mission to Mars and a critical component has broken down; "Door Pin Lock" as shown in the handout. NASA engineers are anticipating

this situation. They want to design features into the parts ahead of time allowing astronauts multiple avenues to provide temporary solutions to this problem. NASA is looking for innovative solutions to fix this problem. So, your task is to provide a temporary fix to this problem satisfying the following condition.

- **The door pin must automatically return to the locked position even when there is no electricity.**

Since the parts are still being designed, you can add or remove features to the parts. NASA will send supplies to the space station with the astronauts. The supplies will consist of a wide variety of materials and tools but NASA has not decided what materials and tools will be needed for this problem. It costs them millions of dollars per pound, so they want to send as little material as possible. So your solutions will help to determine what supplies to send.

Constraints:

- **You cannot use a metal coil spring. NASA is aware of this solution and needs others.**

Your task is to design a temporary mechanism to move the pin back to the locked position.

Generate as many solutions as possible for the given design problem.

Remember that the products in front may or may not help you to generate solutions. Sketch and use words to describe your ideas. There are sheets with the design problem sketch on it. So, please sketch one idea per sheet of paper. If not you can also use the blank paper for sketching your ideas. Also write down

everything even if it does not satisfy the constraint. Generate as many solutions as possible. You will have 40 minutes for this activity. I'll give you a warning 5 min before the time is up. We'll be using different colours of pen to keep track of when the ideas are generated. I'll exchange your pen at regular intervals of time. Remember you can add or remove features into the parts to allow for temporary solutions.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

After 5 min say **"5 min are over. I'll exchange your pen now."**

After the 1ˢᵗ 5 min change pen- give red pen.

After next 5 min change pen- give green pen

After next 10 min change pen- give blue pen

After next 10 min change pen- give maroon pen

Time for next 10 min.

Your time is up now.

Now I'll give you an example of analogy which will be helpful for doing the nest task. Consider the example of Burr and Velcro as shown in the handout. The design of Velcro is based on an analogy to Burr. Two strips of Velcro fasten together just like the spines on a burr.

Your next task is to number the ideas and put an X next to the ones that don't use any of the given products as analogies.

Let me know when you are done.

Once they are done, take back the pen.

__List of features mapped (For all products)__
Give brown pen for this task.

Your next task is to list all the features you used from the given products to generate each of the ideas. Also name the product used next to the feature. The following are a few examples of features.

Geometry/Shape, function, material, physical principles like friction, adhesion, van der Waals force, energy, etc.

Now consider the specific example of an air mattress in front of you. Various solutions are obtained based on this analogy taking into account its different features. Beginning from the top, the punching bag filled with water uses the inflate/deflate feature like the air mattress. The Water dumbbell is a collapsible weight. It is filled with water and emptied and stored when not in use. Again it uses inflate/deflate feature and easy storage feature from the air mattress. The body suit filled with water and the punching bag filled with sand also use the inflate/deflate feature. So, looking at these solutions and features we can state the high level principle as "use of substance available at a place where the device is to be used to make it functional".

"Please list the features taken from the example products below/next to each idea, name the product used next to the feature and also label the features on the sketches." You'll have 5 minutes for this activity.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch.

Once they are done stop the watch.

Product separation

From the set of products in front of you, please separate out the products that you used for generating ideas and keep them on the right side of the table.

Break

You will now have a 5 min break. The restrooms are right there (point in direction)**, and a water fountain is around the corner from them. Please be back on time."**

Products Feature Listing Task (For implemented products)

Keep products (that they used for idea gen) separate and other products as earlier, Violet pen, idea generation sheets and sheets for feature listing (corresponding to the products used for idea gen) on the table

"For the products on the right side of the table list all features you used from that product to generate each of the ideas. Also list five features that you did not use from the product. Please list/describe features in words or sketches. Also label the features on the given picture of the product.

The given sheets have a name and picture of the product and two columns for features not used and features used. Please describe in words or sketches the features not used and features used in the respective columns on the given sheets. You'll have 10 minutes for this activity.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

Time the activity.

Once they are done, stop the watch.

Similarity Rating Task

Give back the sheets of paper from the idea generation (list of features mapped) task to the participants.   Give the sheet with product numbers and names. Give the sheet for similarity rating and Strawberry (sk).

> **Your task is to compare each of the ideas you generated with each product and rate their similarity on a scale of 1-9, 1 indicating low similarity and 9 indicating high similarity.**
>
> **Please compare the ideas and products and rate their similarity in the respective columns on the given sheet and please leave the other unused boxes empty. You'll have 5 minutes for this task.**

Are there any questions before we begin?

Answer questions if any.

You may begin now.

Start the stop watch

Once they are done, stop the watch.

Give another similarity rating sheet, product feature listing sheets, idea gen sheets and red (sk)

Your next task is to do a similarity rating on a scale of 1-9, between the list of features not used during idea generation and the features used, 1 indicating low similarity and 9 indicating high similarity.

Please compare the features not used with the features used and rate their similarity in the respective columns on the given sheet and please leave the unused boxes empty. For example you have to compare "A-1, A-2, so on…and then B-1, B-2 so on." You'll have 5 minutes for this task.

Are there any questions before we begin?

Answer questions if any.

You may begin now.

Start the stop watch

Once they are done, stop the watch.

   1. Now give the idea generation sheets, sheets for listing principle and Pink (sk).

   "Many of the products share one principle in common which solves the design problem. Please list the principle and mark with a star the ideas that use it." You'll have 5 minutes for this activity.

   Are there any questions? (Answer questions if any)

You may begin now.

Time the activity.

Once they are done stop the watch and collect the sheets.

2. Give sheets for high level principle listing task, design problem, idea generation and light blue pen. Give only the analogies and ask to relist the principle- **"Now you are given a printout with pictures of only some of the products. All these products share the same high level principle that can be used to solve the "door pin lock" problem given earlier in the experiment. Please list the principle that the given set of products share in common on the page in front of you and then generate ideas for the design problem based on this principle. Please circle any solutions you have already generated based on this principle." The design problem is the same as before-** Give handout of design problem.

Again, sketch and use words to describe your ideas. Please sketch one idea per sheet. You will have 10 minutes for circling already generated ideas and for generating new ideas. I'll give you a warning 5 min before the time is up.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

After 5 min change pen- give orange pen

Time for next 5 min

Stop the watch.

Your time is up now.

Collect the sheets.

<u>Survey</u>
Give blue pen. **Please fill out the survey.**

Collect the survey.

<u>Interview (Pilots only)</u>
 "I'll ask you now some questions about your experience. This interview will take

about 5 minutes."

1. What do you think about the experiment?
2. What is your opinion about the similarity rating task?
3. Was the design problem clearly stated?

<u>Disbursement</u>
"Thank you very much for your participation in the experiment.

CASH: <u>Hand out payment slips, $20.</u> **"Please fill in your name and UIN. In order to**

receive the cash, please see Michelle Mitchell in the ME office, as stated on the

voucher. Do you have any questions?"

EXTRA CREDIT: Write name and class affiliation down. Do not write date or experiment number down. **"OK, you'll receive the extra credit. Do you have any questions?**

"Then, thank you again for your participation. Please do not talk about the experiment to anybody in Mechanical until after May 31, 2010, as it will bias the results. Have a good afternoon/ evening."

First, Last Name	Class Affiliation

EXPERIMENT SCRIPT

CONDITION 4

Check List

☐ Participant consent forms (2 copies)

☐ Stop watch utensils

☐ Time Recording Sheet

☐ Products (to be given)

☐ Design problem description

☐ Paper for sketching(including hand sketch)

☐ Multiple colored writing(black, red, green, blue, brown, maroon, violet, Strawberry

(sk), Red (sk), pink (sk), light blue pen, orange pen)

☐ Sheets for product feature listing task (features not used & used)

☐ Sheets for similarity rating task

☐ Sheet for writing high level principle

☐ Sheets for list of principle and idea gen (given only products)

☐ Extra paper

☐ Survey

☐ Interview sheet

☐ Stapler

☐ Payment vouchers

Consent

- Keep two copies of consent forms on table

- Black pen

- Keep design problem, blank paper and paper with sketch for idea generation on top right corner and products on the top left corner of the table

As soon as each participant arrives: **Hello!!** "**You can put your backpack close to the wall and please turn off or silence your cell phones.** Show them the work place. **"Please take your seat. We are ready to begin."**

Read the following statement:

"**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 for given design problem, to participate in a five minute interview and to complete a five minute survey at the end of the experiment. The study will require approximately two hours. Please let me know if you have any questions about the study."

Allow participants to read the form, at least three minutes. Answer all questions the participants ask. Wait until all participants have finished reading before proceeding.

Then say, **"Do you have any questions?** (Answer) **If you agree to participate please sign the consent form and keep a copy for your records."**

"I have one request before we begin: Please do not discuss the experiment with anybody in the Engineering Departments at TAMU until after May 31, 2010. The reason is that it will bias the results if a participant knows what the design problem is or what the tasks are."

Sign the consent forms and take them. If wished, sign copies for records.

Design Problem: Door Pin Lock

Your task is to generate as many solutions as possible for the given design problem. You have some products in front of you that may or may not help you to generate solutions. I'll briefly describe and demonstrate all the products.

Show them the product and then describe and demonstrate.

1. Sticky note holder Lid- This is the lid of a sticky note holder. It consists of a latch. When the latch is moved down, the sticky note holder opens. This is the actual product and it works like this.

2. Sticky note flip book- This is a sticky note flip book.

3. Desk Organizer- This is a desktop organizer. It has slots to hold paper and other stationery.

4. Business card holder- This is a business card holder.

Now, I will read out the description of the design problem for which you will generate solutions. A printout is available below the stack of paper on top right corner of the table. Please flip the stack over and follow along as I read.

NASA astronauts are on a mission to Mars and a critical component has broken down; "Door Pin Lock" as shown in the handout. NASA engineers are anticipating this situation. They want to design features into the parts ahead of time allowing astronauts multiple avenues to provide temporary solutions to this problem. NASA is looking for innovative solutions to fix this problem. So, your task is to provide a temporary fix to this problem satisfying the following condition.

- **The door pin must automatically return to the locked position even when there is no electricity.**

Since the parts are still being designed, you can add or remove features to the parts. NASA will send supplies to the space station with the astronauts. The supplies will consist of a wide variety of materials and tools but NASA has not decided what materials and tools will be needed for this problem. It costs them millions of dollars per pound, so they want to send as little material as possible. So your solutions will help to determine what supplies to send.

Constraints:

- **You cannot use a metal coil spring. NASA is aware of this solution and needs others.**

Your task is to design a temporary mechanism to move the pin back to the locked position.

Generate as many solutions as possible for the given design problem.

Remember that the products in front may or may not help you to generate solutions. Sketch and use words to describe your ideas. There are sheets with the design problem sketch on it. So, please sketch one idea per sheet of paper. If not you can also use the blank paper for sketching your ideas. Also write down everything even if it does not satisfy the constraint. Generate as many solutions as possible. You will have 40 minutes for this activity. I'll give you a warning 5 min before the time is up. We'll be using different colours of pen to keep track of when the ideas are generated. I'll exchange your pen at regular intervals of time. Remember you can add or remove features into the parts to allow for temporary solutions.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

After 5 min say **"5 min are over. I'll exchange your pen now."**

After the 1st 5 min change pen- give red pen.

After next 5 min change pen- give green pen

After next 10 min change pen- give blue pen

After next 10 min change pen- give maroon pen

Time for next 10 min.

Your time is up now.

Now I'll give you an example of analogy which will be helpful for doing the nest task. Consider the example of Burr and Velcro as shown in the handout. The design of Velcro is based on an analogy to Burr. Two strips of Velcro fasten together just like the spines on a burr.

Your next task is to number the ideas and put an X next to the ones that don't use any of the given products as analogies.

Let me know when you are done.

Once they are done, take back the pen.

List of features mapped (feature listing for all products)

Give brown pen for this task.

Your next task is to list all the features you used from the given products to generate each of the ideas. Also name the product used next to the feature. The following are a few examples of features.

Geometry/Shape, function, material, physical principles like friction, adhesion, van der Waals force, energy, etc.

Now consider the specific example of an air mattress in front of you. Various solutions are obtained based on this analogy taking into account its different features. Beginning from the top, the punching bag filled with water uses the inflate/deflate feature like the air mattress. The Water dumbbell is a collapsible weight. It is filled with water and emptied and stored when not in use. Again it uses inflate/deflate feature and easy storage feature from the air mattress. The body suit filled with water and the punching bag filled with sand also use the inflate/deflate

feature. So, looking at these solutions and features we can state the high level principle as "use of substance available at a place where the device is to be used to make it functional".

"Please list the features taken from the example products below/next to each idea, name the product used next to the feature and also label the features on the sketches." You'll have 5 minutes for this activity.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch.

Once they are done stop the watch.

Product separation

From the set of products in front of you, please separate out the products that you used for generating ideas and keep them on the right side of the table.

Break

You will now have a 5 min break. The restrooms are right there (point in direction)**, and a water fountain is around the corner from them. Please be back on time."**

Products Feature Listing Task (feature listing for implemented products)

Keep products (that they used for idea gen) separate and other products as earlier, Violet pen, idea generation sheets and sheets for feature listing (corresponding to the products used for idea gen) on the table

"For the products on the right side of the table list all features you used from that product to generate each of the ideas. Also list five features that you did not use from the product. Please list/describe features in words or sketches. Also label the features on the given picture of the product.

The given sheets have a name and picture of the product and two columns for features not used and features used. Please describe in words or sketches the features not used and features used in the respective columns on the given sheets.

You'll have 10 minutes for this activity.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

Time the activity.

Once they are done, stop the watch.

Similarity Rating Task

Give back the sheets of paper from the idea generation (list of features mapped) task to the participants. Give the sheet with product numbers and names. Give the sheet for similarity rating and Strawberry (sk).

> **Your task is to compare each of the ideas you generated with each product and rate their similarity on a scale of 1-9, 1 indicating low similarity and 9 indicating high similarity.**

Please compare the ideas and products and rate their similarity in the respective columns on the given sheet and please leave the other unused boxes empty. You'll have 5 minutes for this task.

Are there any questions before we begin?

Answer questions if any.

You may begin now.

Start the stop watch

Once they are done, stop the watch.

Give another similarity rating sheet, product feature listing sheets, idea gen sheets and red (sk)

Your next task is to do a similarity rating on a scale of 1-9, between the list of features not used during idea generation and the features used, 1 indicating low similarity and 9 indicating high similarity.

Please compare the features not used with the features used and rate their similarity in the respective columns on the given sheet and please leave the unused boxes empty. For example you have to compare "A-1, A-2, so on…and then B-1, B-2 so on." You'll have 5 minutes for this task.

Are there any questions before we begin?

Answer questions if any.

You may begin now.

Start the stop watch

Once they are done, stop the watch.

1. Now give the idea generation sheets, sheets for listing principle and Pink (sk).

   "If the products share a principle in common, which solves the design problem, please identify and list the principle and mark with a star the ideas that use it." You'll have 5 minutes for this task.

   You may begin now.

   Time the activity.

   Once they are done stop the watch and collect the sheets.

2. Give sheets for high level principle listing task, design problem, idea generation and light blue pen. Give only the analogies and ask to relist the principle- **"Now you are given a printout with picture of only one of the products. This product has a high level principle that can be used to solve the "door pin lock" problem given earlier in the experiment. Please list the principle of the given product on the page in front of you and then generate ideas for the design problem based on this principle. Please circle any solutions you have already generated based on this principle." The design problem is the same as before-** Give handout of design problem.

Again, sketch and use words to describe your ideas. Please sketch one idea per sheet. You will have 10 minutes for circling already generated ideas and for generating new ideas. I'll give you a warning 5 min before the time is up.

Are there any questions before we begin?

Answer questions if any. (Record the questions and answers)

You may begin now.

Start the stop watch

After 5 min change pen- give orange pen

 Time for next 5 min

Stop the watch.

Your time is up now.

Collect the sheets.

Survey

Give blue pen. **Please fill out the survey.**

Collect the survey.

Interview (Pilots only)

 "I'll ask you now some questions about your experience. This interview will take about 5 minutes."

1. What do you think about the experiment?
2. What is your opinion about the similarity rating task?
3. Was the design problem clearly stated?

Disbursement

"Thank you very much for your participation in the experiment.

CASH: Hand out payment slips, $20. **"Please fill in your name and UIN. In order to receive the cash, please see Michelle Mitchell in the ME office, as stated on the voucher. Do you have any questions?"**

EXTRA CREDIT: Write name and class affiliation down. Do not write date or experiment number down. **"OK, you'll receive the extra credit. Do you have any questions?**

"Then, thank you again for your participation. Please do not talk about the experiment to anybody in Mechanical until after May 31, 2010, as it will bias the results. Have a good afternoon/ evening."

First, Last Name	Class Affiliation

RULES FOR IDENTIFYING HIGH LEVEL PRINCIPLE

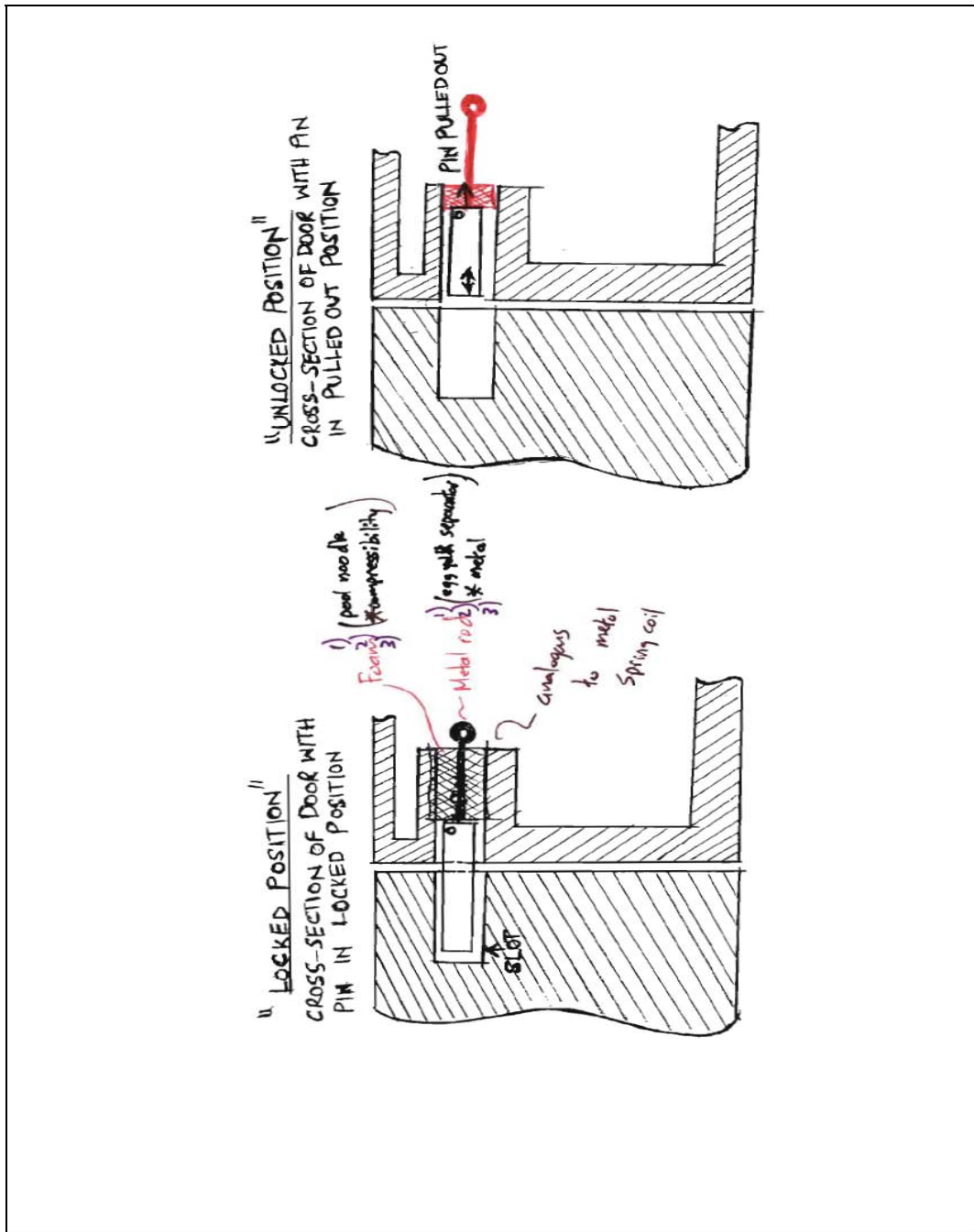High level principle: Energy storage due to material deformation

Other forms:

1. Elasticity

2. Material deformation

3. Mechanical energy storage (spring force)

4. F=KX

5. Store potential energy, return to original position after deformation

6. Something equivalent to the above statements

Not to be considered as high level principle: Spring

a. If the principle stated by the participant is any of the above or its equivalent (implying the same meaning), then rate it as Yes or 1.

b. If the participant has not identified the principle then rate it as No or 0.
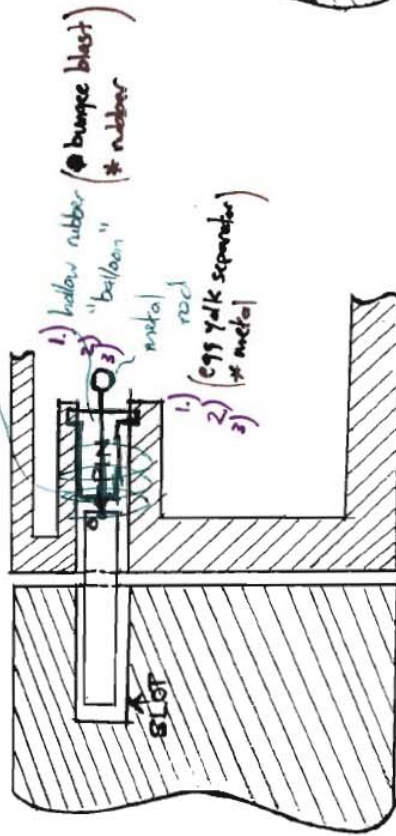
Note: For condition 4, since there was only one product and its three distracters, there was no principle in common among them. So, if the participants stated that there was no principle in common, it was considered as correctly identified principle and was rated Yes or 1.

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SAMPLE SOLUTIONS

"UNLOCKED POSITION"
CROSS-SECTION OF DOOR WITH AN
PIN IN PULLED OUT POSITION

PIN PULLED OUT

When pin is open,
the balloon compresses

"LOCKED POSITION"
CROSS-SECTION OF DOOR WITH
PIN IN LOCKED POSITION
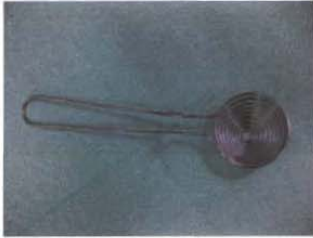
SLOT
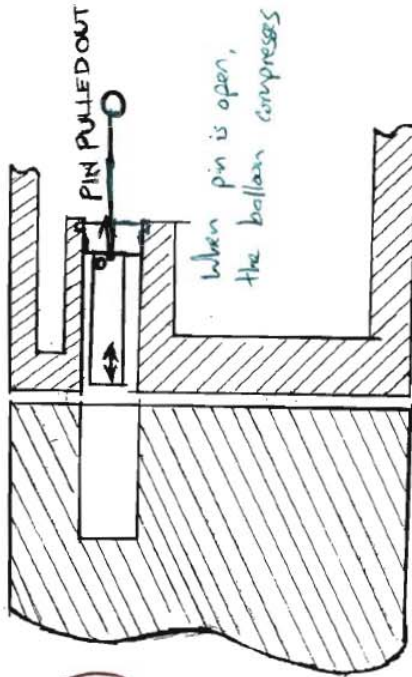
When released the balloon forces the pin back
to the "closed position"

Bungee Blast

Features <u>not</u> used	Features used
A. aerodynamics of fins	1. compressibility of rubber
B. foam	2. a rubber's ability to create a ~~sea~~ leake resistant seal
C.	3. lightweight (density)
D.	4.
E.	5.
	6.
	7.
	8.
	9.
	10.

Egg Yolk Separator

Features <u>not</u> used	Features used
A.	1. coil shape to create a pull handle ⟶O
B.	2. strength (tensile)
C.	3. maintains shape
D.	4.
E.	5.
	6.
	7.
	8.
	9.
	10.

Pool Noodle

Features <u>not</u> used	Features used
A. long shape	1. compressibility of foam
B. hollow inside	2. return to original shape after compressed
C. buoyant in water	3. lightweight (density)
D.	4.
E.	5.
	6.
	7.
	8.
	9.
	10.

Scale: 1= Low similarity - 9= High similarity

Your Idea no	Name of Product	Similarity Rating
1	Flour Sifter	
1	Flour Duster	
1	Egg Yolk Separator	5
1	Constant Force Spring	
1	Paper Airplane	
1	Spiral Chip Holder	
1	Sticky Note Flip Book	
1	Sticky Note Holder Lid	
1	Business Card Holder	
1	Tea Strainer	
1	Tomato Slicer	
1	Bungee Blast	3
1	Desk Organizer	
1	Immersion Heater	
1	Pen Stand	
1	Compression Spring	
1	Pool Noodle	5
1	Burner Coil	
1	Model Rocket	
1	Whisk	

Your Idea no	Name of Product	Similarity Rating
2	Flour Sifter	
2	Flour Duster	
2	Egg Yolk Separator	
2	Constant Force Spring	
2	Paper Airplane	
2	Spiral Chip Holder	
2	Sticky Note Flip Book	
2	Sticky Note Holder Lid	
2	Business Card Holder	
2	Tea Strainer	
2	Tomato Slicer	
2	Bungee Blast	
2	Desk Organizer	
2	Immersion Heater	
2	Pen Stand	
2	Compression Spring	
2	Pool Noodle	6
2	Burner Coil	
2	Model Rocket	
2	Whisk	

Your Idea no	Name of Product	Similarity Rating
3	Flour Sifter	
3	Flour Duster	
3	Egg Yolk Separator	5
3	Constant Force Spring	
3	Paper Airplane	
3	Spiral Chip Holder	
3	Sticky Note Flip Book	
3	Sticky Note Holder Lid	
3	Business Card Holder	
3	Tea Strainer	
3	Tomato Slicer	
3	Bungee Blast	4
3	Desk Organizer	
3	Immersion Heater	
3	Pen Stand	
3	Compression Spring	
3	Pool Noodle	
3	Burner Coil	
3	Model Rocket	
3	Whisk	

Scale: 1= Low similarity   -   9= High similarity

Bungee Blast

Feature not used	Feature used	Similarity Rating		Feature not used	Feature used	Similarity Rating		Feature not used	Feature used	Similarity Rating
A	1	1		B	1	7		C	1	
A	2	1		B	2	4		C	2	
A	3	3		B	3	7		C	3	
A	4			B	4			C	4	
A	5			B	5			C	5	
A	6			B	6			C	6	
A	7			B	7			C	7	
A	8			B	8			C	8	
A	9			B	9			C	9	
A	10			B	10			C	10	

Scale: 1= Low similarity - 9= High similarity

Pool Noodle

Feature **not** used	Feature used	Similarity Rating	Feature **not** used	Feature used	Similarity Rating	Feature **not** used	Feature used	Similarity Rating
A	1	1	B	1	1	C	1	1
A	2	1	B	2	3	C	2	2
A	3	1	B	3	6	C	3	8
A	4		B	4		C	4	
A	5		B	5		C	5	
A	6		B	6		C	6	
A	7		B	7		C	7	
A	8		B	8		C	8	
A	9		B	9		C	9	
A	10		B	10		C	10	

List the one principle that many of the products share in common, which solves the design problem

− compressibility ~~& rubber~~

~~elasticity of~~
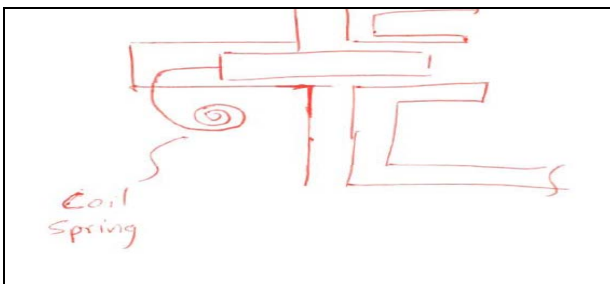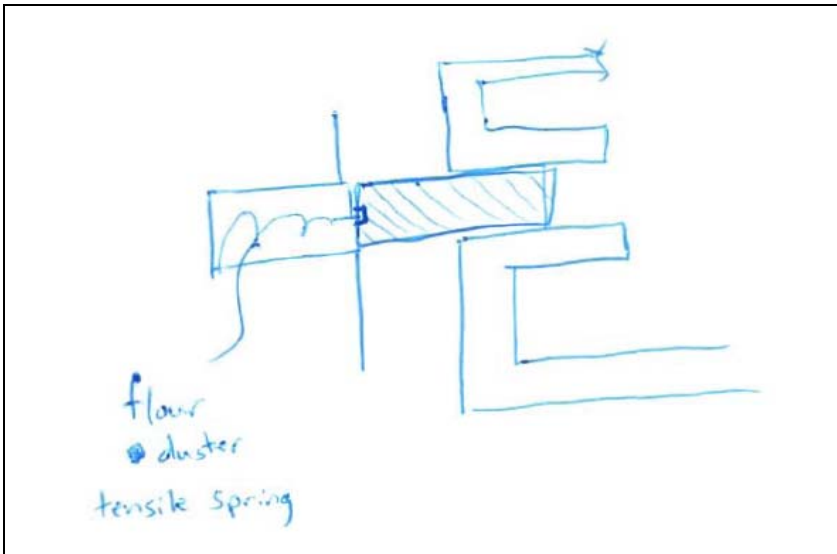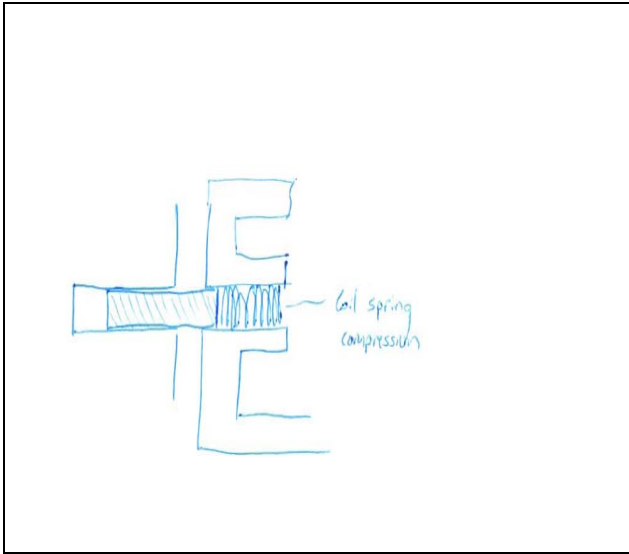
List the principle that the given set of products share in common, which solves the design problem.

Elasticity

coil spring compression

flour
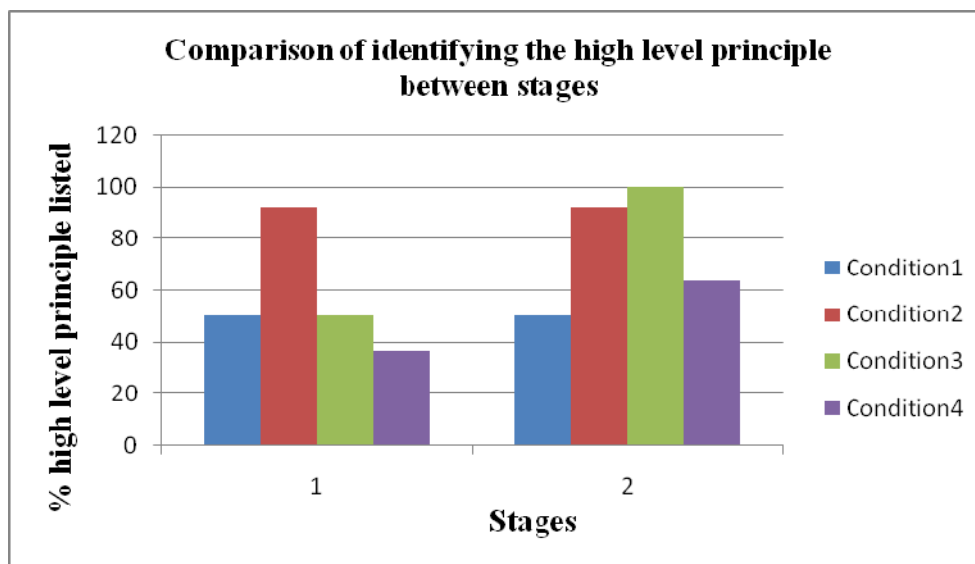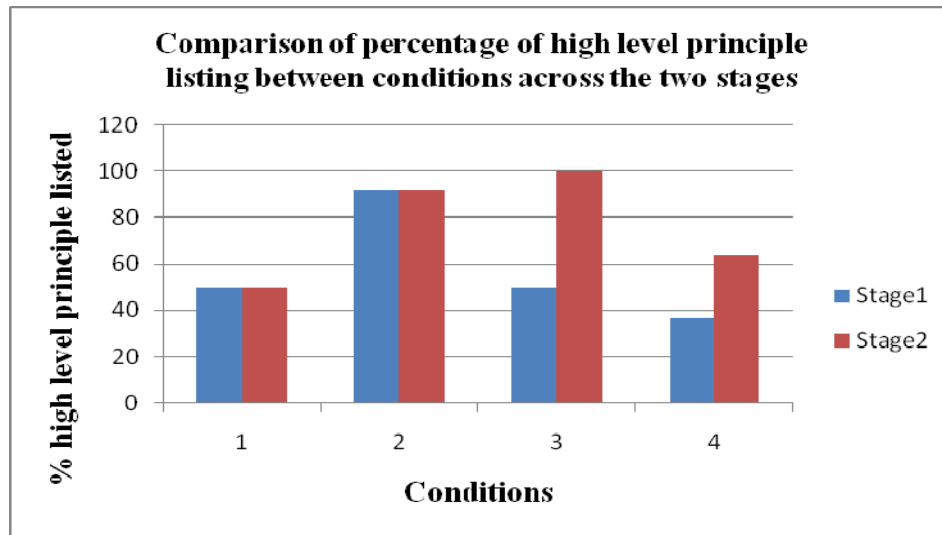duster
tensile Spring

Coil Spring
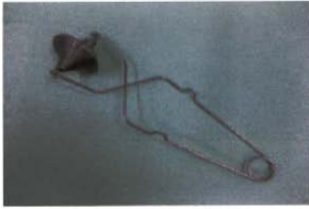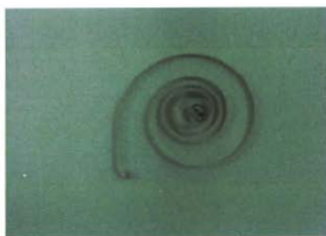
RESULTS FOR SECOND STAGE OF PRINCIPLE LISTING

The table and the graphs below show the results for the second stage of principle identification. As can be observed from the graphs below, there is an increase in the identification of the high level principle between the stages in condition 3 and condition 4. This implies that in conditions 3 and 4, when the participants are presented only with the products in stage 2 and told that the products have a high level principle in common, the percentage of identifying the high level principle increases as against stage 1 which has both products and distracters. Also the results between the stages in conditions 1 and 2 remain the same as these conditions have only products and no distracters. These results were expected.

	% of high level principle listed	% of high level principle listed
	Stage 1	Stage2
Condition1	50	50
Condition2	91.67	91.67
Condition3	50	100
Condition 4	36.36	63.63

Comparison of percentage of high level principle listing between conditions across the two stages

Comparison of identifying the high level principle between stages

APPENDIX C

CODING FOR PRIOR ANALOGY EXPERIMENT

AIRMATTRESS ANALOGY

Design Problem- Exercise Equipment		
Source	Characteristic mapped	Solution
Air mattress	Inflate/ Deflate	Water Dumbells, Water floaties, Plastic bag with gel
	Using substance available at given place	Inflatable ball
	Easy to store	Sand bags/ weights
	Collapsable	barbell
	Resistance	Ankle wts
		Collapsable weight bar + weights
		Inflatable mat
		Suitcase filled with water/ clothes
		Boxing Gloves
		Air / Water balloon
		Punching bag with water
Air mattress + toy		flour balloon
Air mattress		Body Suit

SOLUTIONS
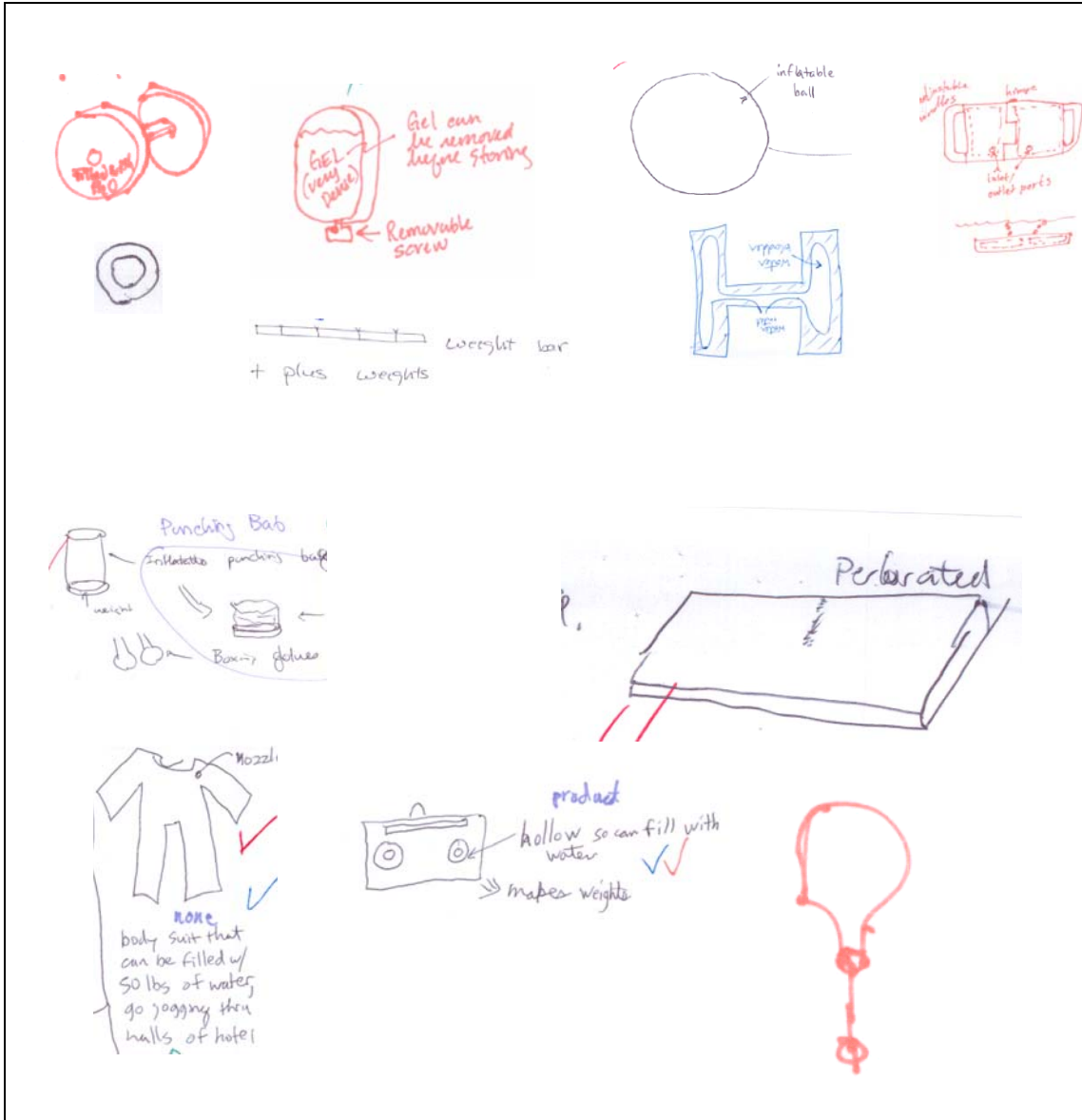
TOY ANALOGY

Design Problem- Flour Sifter		
Source	Characteristic mapped	Solution
Toy	Contain Flour	Two part wire ball
	two halves	
	Geometry	
	Easy storage & transport	
	open and close	
	pull apart to open	Container with hinged doors
	Force applied to open	
	** blocks inside the toy sphere	
	**push instead of pull	
	Holes	

SOLUTIONS
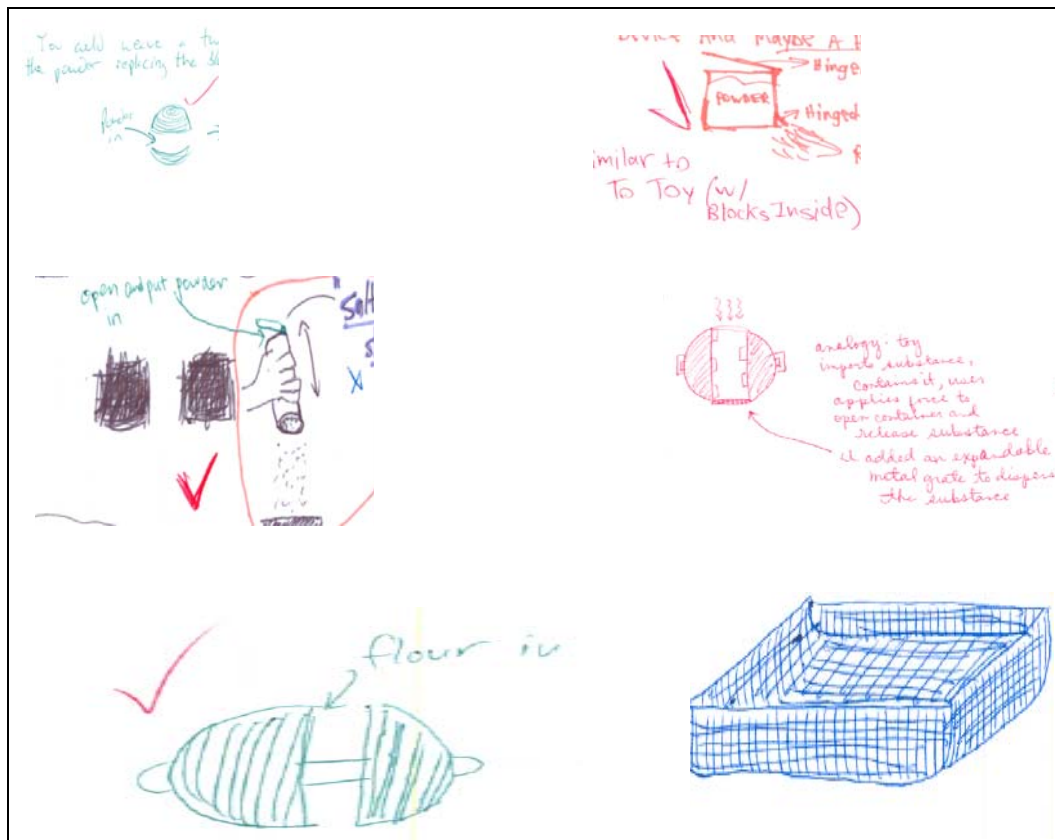
VITA

Apeksha Gadwal obtained her Bachelor of Technology degree in mechanical engineering from Jawaharlal Nehru Technological University, Hyderabad, India in May 2007. She pursued her graduate studies at Texas A&M University in mechanical engineering from August 2008 and received her Master of Science degree in August 2010. Her research interests include design-by-analogy and innovation in design.

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