ABSTRACT

Title of Document:	DESIGN THINKING: COGNITIVE PATTERNS IN ENGINEERING DESIGN DOCUMENTATION
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Engineering design is an integral resource that on the surface uses creative, scientific, and process knowledge. Over the years many research driven improvements have been made to the methods and tools used for crafting the engineering design profession. Some progress has been made in exploring the cognitive processes, reading between the lines, and thinking about design thinking. This information is valuable to engineering designers in visualizing and performing the product development process.

This dissertation is interdisciplinary in nature. The goal of this research is to apply cognitive research techniques to engineering design documentation to understand what happens in the mind during the design process. This research can be considered as an exploratory study of uncovering cognitive processes during design by developing a coding scheme that is applied to student and professional design journals. A successful cognitive coding scheme can be used in different domains and

leads to development of new metrics for examining journal activities. This first study will enable future work aligned with the larger research goal of improving the understanding of design thinking.

Engineering design documentation is one method of revealing insights into the mysteries of the mind. Design journals are used in this study combined with a Cognitive Coding Scheme created by the author to explore design thinking. This dissertation focuses on identifying patterns in cognitive behavior of engineering designers. Design documentation is also analyzed for insights on attitudes towards design journaling.

This dissertation will make a contribution to the field of engineering design research by presenting a cognitive coding scheme capable of revealing insights into the mind of the designers.

DESIGN THINKING: COGNITIVE PATTERNS IN ENGINEERING DESIGN DOCUMENTATION

By

Sophoria Nicole Westmoreland

Dissertation submitted to the Faculty of the Graduate School of the
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Advisory Committee:
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Dedication

But because God was so gracious, so very generous, here I am. *1 Corinthians 15:10*

I proudly pronounce that this dissertation is dedicated to my parents, Rev. Henry and Anita Westmoreland of Katy, Texas for all their loving support and unfailing understanding provided to me throughout my entire life.

To the memory and legacy left by my great-grandmother, Mrs. Imogene Elizabeth Evans, who transitioned 14 months after I started my graduate program at Maryland. I walk with my head held gracefully high, my back bone straight, and my feet firmly planted in the Word of God because of you.

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- I also wholeheartedly dedicate this dissertation to my entire Metropolitan Baptist Church family who have constantly interceded to God with prayers

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- To be blessed abundantly with lifelong friends is God's gift to me, and to these friends I extend this dedication with my gratitude for loving me in and out of season. Starting from Wilson Hall at Tennessee State University to Clark Atlanta University to Georgia Institute of Technology to University of Maryland all my friends have whole heartedly supported by life goals. To the lovely ladies of Alpha Kappa Alpha Sorority, Inc. - we help each other for we know there's no other. To my family at Good Hope Missionary Baptist church- thanks for your prayers, support, cards, visits, and the Waffle House.
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Chapter 1: Introduction

Engineering design cognition studies make up a fundamental body of research that seeks to understand the mind's processes and abilities used during the design activity. According to Cross et al. design activities encompass the highest possible human cognitive levels [1]. Several researchers have focused on research in engineering design [1-21]. Atman et al. of University of Washington highlights that the body of work in cognition research in engineering design is evolving [4]. Research efforts similar to this dissertation have provided the foundation for the insights into the cognitive processes of engineering designers. This dissertation is situated in this evolving field and makes a contribution to its continuing progression.

1.1 Research Motivation

The art of innovation is essential to creating a dynamic society and securing the future prosperity of a nation. All humans design at some level whether it is designing a GPS-guided missile or designing a nursery for a new baby. During the design process knowledge is applied to create something "new" to the designer. The person designing is manipulating knowledge in his or her mind, alone or in consultation with others, and using external tools to create the final design outcome. Examples of external design tools are paper, pencils, materials, adhesives, measurement devices and computer programs.

According to Alexander et al. (1991) knowledge is "an individual's personal stock of information, skills, experiences, beliefs and memories" (p. 317) [22]. While engaged in the design process individuals are retrieving knowledge from two sources to create the final design: working knowledge and domain knowledge. Domain knowledge is defined as the broader realm of the knowledge an individual possesses about a particular field [23]. Working knowledge is a sub-section of domain knowledge that pertains to knowledge of how things work but not necessarily why. Working knowledge can come from a variety of sources such as a freshman introductory engineering design course or a Martha Stewart interior decorating book. From the time we are born we are gathering information via our five senses to perceive our environments and build this space of working knowledge. Once this information has entered the mind various mental activities and cognitive processes are performed in the brain (called *cognitive activities*) to decode the information and organize it in the mind. The mind's arrangement of this information is used to energize the art of innovation.

Over time engineering designers develop strategies to fulfill their work duties efficiently by means of working knowledge and practice. Classroom trained engineering designers begin this strategy development at the university level. The profession of engineering is purposed to design new technologies, products, and systems that solve practical problems and make life easier. Ask any inventor: "*How did you come up with that awesome idea for new technology"?* This question is often answered with a shrug and a simple "*I don't know, it just came to my mind"*. Some of these new ideas seem to be the result of divine inspiration even when design tools and methods are strictly applied. Other ideas are clearly the result of the vigilant application of an effective design methodology. When successful new technologies are presented to the market they are often met with jaw dropping amazement deserving of such innovative brilliance, as Steve Jobs did at many Apple, Inc. shareholders meetings presenting new products. Design documentation such as design journals, verbal protocol data, papers, and sketches can reveal an abundant amount of understanding about the designer's behaviors during the design process. It is possible to use design documentation to create new tools to alleviate the mental burden of designing something "new".

To increase knowledge in engineering design, new methods are needed to understand the cognitive operations and patterns used in the mind. Some common cognitive operators used during design are analogies, search, questioning, and problem statement clarification. As a way to understand the mind's activities during design, the field of psychology is a rich resource. Psychology literature provides an abundant source for understanding the cognitive aspects that traditional design research often overlook.

Engineering design researchers have an active history in the study of cognitive processes. Topics appearing in cognitive research in engineering design include development of expertise and individual differences in engineering design [4, 24-28], analyzing design activity [1, 29-33], cognitive models in engineering design [34, 35], cognitive processes in engineering design [11, 36], and engineering design learning[3, 37, 38]. The field of engineering design research that focuses on understanding the cognitive processes of designers is evolving and being promoted in conferences and technical peer reviewed journal articles.

1.2 Problem Description

Engineers need good design education and training to do quality design. Good design education is the foundation for solid design practices, innovation, and forward thinking in a global society. Quality engineering design happens when designers are able to successfully use their technical, mathematical, and analytical knowledge to solve a problem or address a societal need. In 1991 the National Research Council published the statement "employers find recent graduates to be weak in design" (p. 2) [39]. With new legislation like *The American Invents Act* and The White House's *Educate to Innovate* initiative the stakes for engineering designers are higher than they have ever been. In President Barack Obama's *Strategy for American Innovation* (2011) he highlights the need to accelerate, support, catalyze, and promote innovation in order to "drive future economic growth and continue to lead on the global stage" [40]. The need to drive innovation forward with products that are smaller, faster, and cheaper is exponentially increasing, not to mention products that also have aesthetic features that promise market share. The quality of life that is desired for the future depends on the invention of new cars, computers, cell phones, cameras and other gadgets all while decreasing the manufacturing time and increasing the life cycle. Innovation that will create clean energy sources, reduce nuclear threats, eliminate financial crises, and avert the depletion of earth's natural resources will sustain our way of living for many years to come. Securing the innovation pipeline with quality design education is essential.

The National Research Council (1991) defines engineering design as "the technical element in the product realization process that involves the application of knowledge and techniques from engineering, science, aesthetics, economics, and psychology in establishing specifications for products and their associated production processes; the technical processes by which engineering descriptions and specifications are formulated to ensure that a product will possess the desired behavior, performance, quality, and the cost (the reverse of engineering analysis)" (p. 82) [39].

It is important to note that not all engineering graduates will become full-time designers; the vast majority will be involved in some part of the engineering design, production or service processes. Society as a whole has high expectations of engineering graduates; this increases the need to properly train them in the design process. To overlook providing them with a quality engineering design training would mean overlooking the significant need for future inventors and innovators that will rely on effective design skills. Undergraduate and graduate engineering education serves as a foundation for high-quality practice, effective teaching, and significant research in engineering design [39]. Engineering firms' intellectual property depends on the ideas that exist in the minds of their engineering designers [41]. Such proprietary knowledge is the basis for innovative products and designs that are the result of the designer's proficient skills and effective training.

The difficulty with delivering the best design education to engineers is that we don't fully understand the mental processes that occur during design. The more knowledge that design theory and methodology research can uncover about quality design thinking, processes, and practices of working designers the better the tools and curriculum interventions are that can be developed. The obvious challenge is that we can't see with our eyes the cognitive operations of the mind. This requires looking for evidence of these cognitive activities in other places, such as engineering design documentation.

1.3 Goals of the Research

This dissertation is interdisciplinary in nature. The goal of this research is to apply cognitive research techniques to engineering design documentation to understand what happens in the mind during the design process. This research can be considered as an exploratory study of uncovering cognitive processes during design by developing a coding scheme that is applied to student and professional design journals. A successful cognitive coding scheme can be used in different domains and leads to development of new metrics for examining journal activities. This first study will enable future work aligned with the larger research goal of improving the understanding of design thinking. The broad impacts this dissertation has are t

According to the ED 2030 Strategic Plan for Engineering Design (2004): "The key to successful design in general requires a deeper understanding of and support for the creative cognitive processes; also the mapping of such cognitive models onto design tools and methods is a critical research direction" (p. 8) [20]. This statement is in line with the goals for this dissertation and future investigations that will follow. The longer term research agenda will benefit professional engineers by providing details about the cognitive activities that can supplement the education, abilities, and ideas they already possess. This research track will also assists designers in identifying best practices from experts and to create effective training programs for novice engineers. A deeper understanding of the mind may be beneficial when the design task changes from project to project.

1.3.1 Research Questions

This work's goal is to investigate the following 4 research questions as part of a larger research agenda:

1. How can cognitive activities be identified from studying engineering design documentation from the classroom and in professional practice? This question relates to finding a systematic way to relate what is written on paper with what is happening in the mind. This research question is addressed in Chapter 3 by detailing the methodology for creating the cognitive coding scheme and also including verification and validation methods.
2. What cognitive activity sequences exist to aid designers in developing an enhanced understanding of design problems? This question is about locating patterns of design behavior across a group, looking at what similarities exist and what are the differences. This research question is addressed in Chapter 5 where the results from the cognitive coding scheme are presented and also in Chapter 7 where sequences of journaling behavior are the topic.
3. How do engineering design students respond to using hand written design journals within a capstone design course and why? This question is important for the future administration of design journals in engineering courses and the possibilities that exist to enhance that experience using the results from this

dissertation. This research question is addressed in Chapter 5 in the quantitative results section.

4. What can engineering design documentation reveal about participation within and between capstone design teams design activities? This question will reveal the team activities and behaviors that result from this dissertation. This research questions is addressed in Chapter 4 where the metrics for tracking concepts is introduces and then again in Chapter 5 where the results are presented.

1.3.2 Dissertation Format

This dissertation is organized as follows: Chapter 2 reviews literature on cognitive processes, design studies, and implementing engineering design journals as a research method; Chapter 3 is methodologies used for this dissertations cognitive coding scheme including verification and validation steps; Chapter 4 is the design journal coding process used in this dissertation; Chapter 5 is the results from a 3-semester student study using design journal and subsequent qualitative findings; Chapter 6 reveals the results from the study of professionals engineering design documentation including qualitative data; Chapter 7 compares the students and the professional design engineer on design behavior and design transitions and Chapter 8 includes discussions and contribution from this dissertation and future work.

Chapter 2: Literature Review

The research presented in this dissertation is interdisciplinary in nature. The nature of engineering design is complex; therefore design research is just as complex [42]. Studying human behavior in design starts with cognitive psychology because of its long history of analyzing human behavior. Examining the practice of designers will reveal the true influences in behavior and external design representations.

The following sections detail research studies and review related literature. First, overviews of psychology, educational psychology, cognitive psychology, cognitive science, and biology, which all have a focus on cognitive processes, are highlighted. Second a historical perspective of the basic nature of design are defined through the literature of Simon [43], Visser [44], and Schön [45] (with interpretations from Dorst and Roozenburg [46]). Third relevant design behavior studies in engineering are described briefly. Next design cognition studies in engineering that present design thinking results related to this dissertation are discussed. These studies include Grenier, Atman, Lindemann, Stempfle, Shah, and Williams. Finally applicable design documentation studies in engineering are presented and the importance of writing across the engineering curriculum is presented with relation to this dissertation.

2.1 The Mysteries of Cognitive Processes

William James (1890) says it plainly "the first fact is that thinking of some sort goes on" (p. 6) [47]. James goes into details about characteristics of thoughts, awareness of thoughts, and connections between thoughts and the outside world. Cognitive processes control everyday life and daily activities [48]. The study of cognitive processes has a goal of revealing how people organize and use knowledge in daily life or work situations. There are many mysteries surrounding cognition because a map of the mind's thoughts is an unobservable one. Even though this is true, researchers in various fields have a long history of successful studies of the use of knowledge and thoughts [49-52]. Such studies increase the understanding of the unknown workings of the human thinking processes to maximize the usefulness of tools and methods that promote metacognitive strategies. Underneath the umbrella of fields that study cognitive processes are the interdisciplinary research areas shown in Figure 1. It is important to note the interdisciplinary features of these fields. They do not simply fit into the bounds of a particular area of scientific investigation. This dissertation uses definitions and theories as supporting resources from these fields.

Starting with psychology as the foundational knowledge base, Figure 1gives an overview of fields related to this research and topics included in each area. It is important to highlight the similarities which can be seen in the overlapping parts of the circles. The central theme in all these branches of cognitive research is a focus around studies concerned with the mind. Other overlapping research agendas in these sciences are learning, behavior, representations, human cognition, and language. The research perspectives and how the questions are framed relate to the specific theories about the mind that are widely accepted in that particular field or sub field. A detailed historical perspective on cognitive studies in design can be found in the appendix.

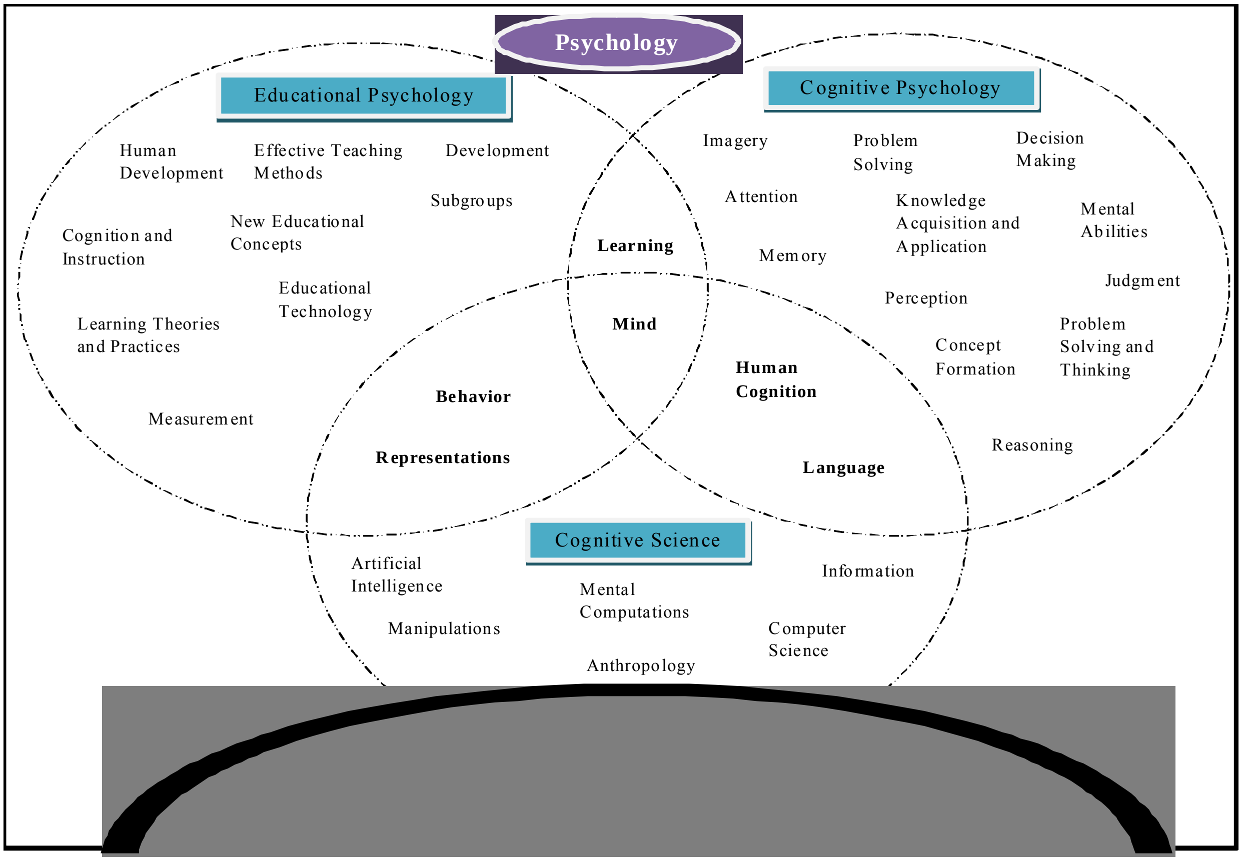


Figure 1: Psychological Disciplines [53-57]

2.2 Cognitive Fields of Study

The following is a detailed list describing of the cognitive based fields including widely accepted definitions and examples of research questions related to that particular field.

Cognitive Psychology is a branch of psychology that deals with mental processes and how they occur inside the mind [55]. Cognitive Psychology researchers study perception, attention, memory, imagery, and language [56, 58]. Anderson describes cognitive psychology as being dominated by information-processing approaches that analyze using ordered stages [59]. The goal of cognitive psychology is to use the scientific method to understand mental activity and improve intellectual training and performance [56, 59]. Cognitive psychology overlaps educational psychology but is more concerned with specific functions of the mind. Examples of questions cognitive psychologists seek to answer are:

- Why can I remember my bank account number, e-mail passwords, and house alarm password but I cannot remember where I parked my car an hour ago at the mall?
- Why are certain people better at multitasking than others?

Educational Psychology involves advancing theories about the human mind and the application of those theories to "*add value*" to the mind [60]. Educational psychologists study teaching and learning phenomena. Social psychology plays an important role in the field of educational psychology because learning occurs in classroom settings which are affected by the social environment. Example questions educational psychologist would seek to answer are:

- What would a model of learning look like for a novice engineer compared to an expert engineer? [61]
- How do gifted students learn math?

Neuroscience is an interdisciplinary field that seeks to understand the human brain and the nervous system. One goal of neuroscience is to apply scientific knowledge to develop improved disease treatments and cures [62]. Neuroscientists look at the cellular and molecular levels within the nervous system, neuronal systems for sensory and motor function, and the basis of higher order processes of cognition and emotion [63]. Example questions those neuroscientists seek to answer are:

- What activity happens in the brain during sleep?
- How exactly are memories put in storage in the brain? [63]
- How does information flow to the brain when the body experiences physical pain?

Cognitive Science has a goal of understanding the nature of the human mind through the interdisciplinary study of artificial intelligence, linguistics, anthropology, psychology, neuroscience, philosophy, and education [64]. Cognitive science is a broad field which also includes some areas of cognitive psychology. It is important to note the abundant use of computer simulation of cognitive processes used in cognitive science. Anderson states that cognitive science first appeared in 1976 with the appearance of the journal *Cognitive Science* [59]. Example questions those cognitive scientists seek to answer are:

- What would a map of the brain look like?
- What is the measure of the short term memory span in young adults for long and short words?

Cognitive Engineering is a type of applied cognitive science. This field exists to apply what is known from science to the design and construction of machines [65]. Cognitive engineering emphasizes the application of knowledge and techniques from cognitive psychology and cognitive science to the design of the human-machines systems [66]. Example questions those cognitive engineers seek to answer are:

- What cognitive tasks are most frequently used in complex environments such as military combat?
- What factors influence the decisions of trauma nurses in the Emergency Room?

2.3 Behavior Studies in Engineering Design

There exist a wide variety of methods for researching designer behavior such as verbal protocol analysis [4-6, 10, 36], design prompts [7], direct observation [1, 11], coding design journal content [30, 32, 67, 68], and interviewing designers [69]. The methodology used to study design activity often relates to the anticipated results. The primary goal of design behavior studies is direct observation of designer behavior. While cognitive findings may surface from such studies, this is generally not the main research objective.

Design behavior studies are important for this dissertation because they are the original type of design studies, they inspired the methodologies of cognitive design studies, and their findings have increased the understanding of the design process. Design behavior studies research the behavior of individual student designers, student design teams, individual professional designers, and professional design teams.

Mixed methods studies present comparisons and follow-ups with students across their educational class standing [4-7, 69-71]. Similar studies group freshman and seniors together, monitor behavior from freshman to senior year, compare seniors beside freshman, and study student's at the sophomore and junior year. Professional engineering designers are often studied in parallel to a model of proficient design behavior. The studies reviewed here are both in-comparison (professionals to professionals/ students to students) and out-comparison (professionals to students). Design behavior research is also present in research theories related to the apparel design process [72]. The engineering design process has broad applications for creating innovative solutions in other design disciplines.

In a 2007 publication Atman et al. compared 19 professional engineers during the design processes with 50 undergraduate engineering students [4]. The students and the professionals designed a neighborhood playground in a lab setting for 3 hours and were video and audio recorded. Each group was given the identical design task and the same requirements for completion. The study is modeled after a classroom study done by Dally & Zhang at the University of Maryland, College Park [73]. Half of the students in the study were seniors and half were freshman and all were identified as engineering majors. The Atman et al. study presents the design process occurring three stages in the engineering career pathway-freshman, seniors, and professional engineers. Verbal reports were collected during the sessions that focused on problem scoping, project realization, idea generation, transitions, and total time on design activities. Verbal protocol analysis method was used for analyzing the transcribed audio data. Five stages of the design process were the focus - problem scoping, project realization, alternative solution generation, distribution of activity over time, and solution quality. A coding scheme was created to reflect engineering design process models that were being used in the classroom to teach design to engineering students. A finding from the Atman et al. study that is relevant to this dissertation is that the time professional engineers spend in problem scoping and project realization are greater than the students. This is interesting because this is something that is expected to be found in the results from this dissertation using the coding scheme that we have created. Also the rigorous methodological treatment of the research, the similarities in comparing students with experts, and the findings that have implications for both professionals and students designers are similar to the work done for this dissertation. Atman et al. did not specifically set out to reveal cognitive design behavior which is a gap this dissertation will fill in order to increase understanding of the design process.

Professional industrial designers were the focus of a study done by Henderson to analyze the role of online (electronic) and on paper (sketchbooks) visual representations in day to day professional engineering behavior [74]. Examples of electronic representations include CAD drawings and FEA simulations. Examples of paper representations include sketchbooks, blueprints, notepads, and back of the envelope drawings. Henderson observed the play between electronic and paper visual representation uses by professional designers. Henderson came to the conclusion that neither electronic nor paper visual representations have a complete advantage over the other at enhancing the creativity of the design engineers. An advantage to using electronic and paper was the ability to look at more than one visual at a time increased the comprehension of the design engineer. Also Henderson found that during the analysis phase of the design process paper was great for rapidly capturing preliminary ideas. The foundational work done by the author of this dissertation was on visual representations used in senior capstone design reports over 5 semesters at the University of Maryland [75]. Henderson's work concludes that both the online and on paper visual representations are helpful during the design process which is important for this dissertation because on paper visual representations are noted to reveal as an integral part of design behavior.

During the conceptual design phase of the design process Tang et al. conducted a mix methods study on design behavior [76]. The study compared the differences between the digital environment and the traditional pen and paper design environment with 20 students working in teams of two. The students designed a USB flash drive that also could operate as a personal weapon. The digital environment was a separate but shared experience for the students using technological sketching and communication software. Both environments were audio and video recorded and transcribed for analysis by applying the function-behavior-structure (FBS) coding scheme [10, 77]. The students also did a two minute poster presentation in front of expert judges. Using the judge's scores and the analysis of the design session transcripts Tang et al. concluded that the digital and traditional environments produced comparable design ideas. Tang et al.'s study is important to this dissertation because it highlights the importance of the transitions between the design segments and that can also be done with our cognitive coding scheme. We can present similar comparisons using our coding scheme this will validate our coding scheme as capable of producing at the least comparable results to published studies.

2.4 Cognition Studies in Engineering Design

Cognitive protocol studies are similar in many ways to design behavior protocol studies except that they focus on researching unobservable behaviors and abstract level cognitive activities.

For example capstone design course studies with a focus on cognitive activities of designers have been done by investigators such as Grenier and Sobek.

Grenier et al. (2007) analyzed design journal sketches and notations of capstone design students to learn "how students are learning and practicing design" (p. 1) [78]. A design study was done in the summer 2006 at University of Maryland by the RISE (Research in Science and Engineering) research team on 12 students design journals in a senior capstone design course. A 2006 study report by Jain and Sobek [29] was used as the inspiration for the RISE (Grenier et al.) study. Sobek (the second author of [5]) in fact provided research support during the RISE study by contributing design journals from his senior capstone design students at Montana State University. Grenier et al. shows that positive links exist between sketching and cognitive processes. The journals of both capstone design teams studied (2 teams, 6 students per team for 12 total student design journals) displayed high numbers of two cognitive operators: generation and exploration. Motivating the students to use the journals was noted as hard because the students did not understand the benefits they would gain from using them. The analysis of design journals in the Grenier et al. (2007) study presents promise for learning more about the cognitive processes of engineering design students. Grenier concluded "research into cognitive processes is necessary and has an extended and motivating future" (p. 9).

Another example is freshman cognitive protocol studies that study mainly first year students design activities and design learning environments. Atman et al. has one such reported study in the book *Design Knowing and Learning: Cognition in Design Education* [6]. Atman et al.'s paper evaluates 4 verbal protocol studies and presents some results and cognitive implications for engineering design education. Her study was done using verbal protocol analysis, which is a popular method for studying the design process and also for understanding cognitive activities in any field. Sixteen freshmen participated in a design project for approximately 2 hours at the beginning and then again at the end of their freshman year. (The same students both times) The objective of the Atman et al. study was to look at the impact that one semester of engineering studies had on design knowledge. Positive implications were found regarding effort, transitions steps, and criteria considered yet no definitive results for design quality. A level of effort exerted by the students was calculated based on the number of words spoken during the design process and compared between pre and post freshman studies. Atman's novel research supports this dissertation by showing that it is possible to extract information about the cognitive activities during the design process.

In the same book, *Design Knowing and Learning: Cognition in Design,* as Atman's study other empirical studies on design thinking are presented[33]. One question important for this dissertation, which is a topic in the book: How do we filter cognition from external articles? This dissertation proposes a way of doing that through a detailed cognitive coding scheme and will present evidence of the findings. The book authors and editors (several papers were contributed for the book) point out well known models from cognitive psychology that can be applied to design thinking such as mental imagery and visual reasoning [79], analogical reasoning [80], reminding, thinking and creativity, and metaphorical reasoning. Cognitive psychologists have created models of information processing that can form a foundation for design thinking research [55-59]. The cognitive models will help answer the *How* question in design thinking research. This dissertation will use external representations of design activities recording during the design process to answer the *How* question about design thinking.

In the book *Human Behaviour in Design* Lindemann et al. evaluate the density of design moves (comparable to the design segments found later in this dissertation) and the interconnectivity with the effectiveness of design [24]. The goal was to understand the differences between successful and unsuccessful design performance. *Human Behaviour in Design*, which is actually edited by Lindemann, includes various authors from engineering design and cognitive psychology that have come together to discuss design thinking and strategies for engineering design using mixed methodologies of individual designers as well as design teams. In the same book a study was presented on sketching and the benefits of creating external representations during the design process. Sketching was found to relieve short-term memory by revealing contradictions or incomplete ideas that the mind may not have noticed. It was also reported that cognitive design research such as this dissertation is important for informing design, facilitating design, and improving our understanding of design in order to create better tools and methods for doing design. Lindemann et al. highlight the gap that exists in more than one research area between descriptive research and prescriptive research but acknowledges the recent improvements in the gap. As we progress in this field of design studies Lindemann acknowledges that there exists a need for building our knowledge foundations[24].

Other similar design cognition studies report the field of study of participants but not their class standing, yet are relevant to this dissertation. One such study was done on team communication by Stempfle (2002) where he studied the thinking process of student design teams, which he notes as “a most important issue in design research” (p. 473) [70]. Looking at three groups of mechanical engineering design students (4-6 students per team) designing a sun planetarium for six hours while recording the team communication. A coding scheme was created to analyze the team communication in order to create a model of design team activity. According to Stempfle (2002) four basic operations define thinking in design: “generation, exploration, comparison, and selection” (p. 476). These four cognitive operations were mapped to different stages of the design process to create the model of design team thinking. Stempfle’s study produces three concluding results. The first is that structuring the group development is significant in design team’s success. The second is that 90% of the design team’s time was spent in the solution space. The third is a two-process theory on design team communication for evaluating alternative design solutions is shown in Figure 2.

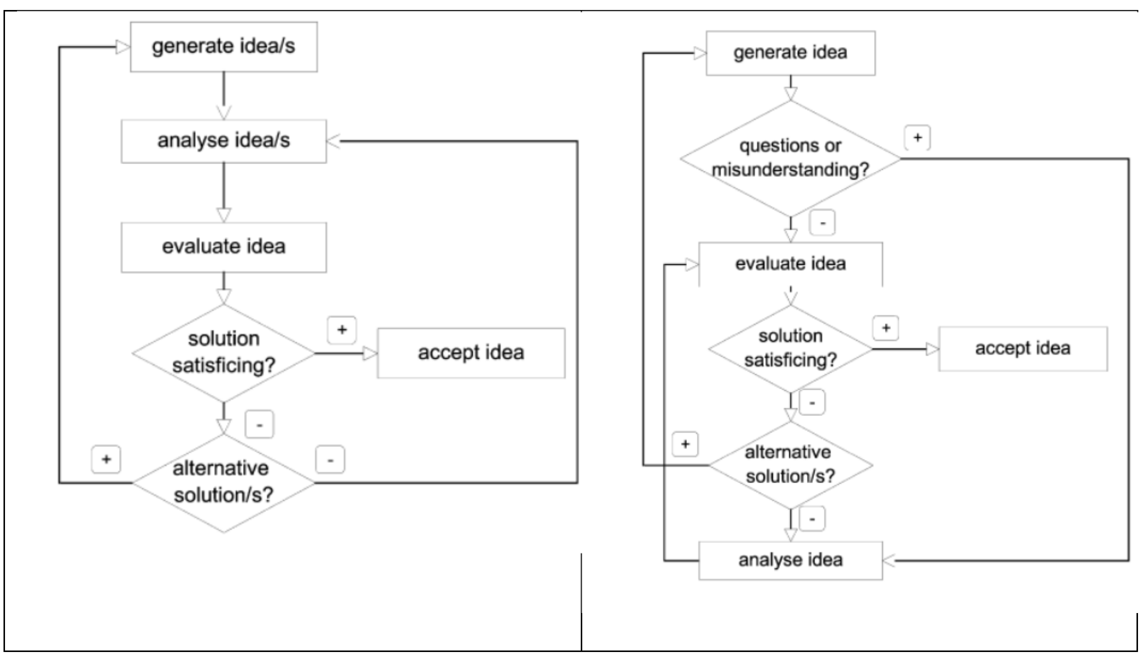


Figure 2: Stempfle's Proposed Models of Design Team Thinking [70]

The theory behind the two processes is grounded in what the three teams in the study used: (1) quick evaluations of project ideas and (2) immediate analysis of ideas, both with pros and cons. Stempfle highlights the need for design research that takes into account the environment in which the professional designer is accustomed and understands the design process from that perspective to create tools to assist the designer. This dissertation uses design journals as a tool not only for collecting data but also as a tool to teach the students to properly reflect and record during the design process, which Stempfle (2002) highlights as a valuable tool for "modifying inadequate thinking" (p. 496). The experienced based learning of creating an informal design journal is a highly valued benefit that is expected to be a result from all participants in the research for this dissertation.

Fully integrating the psychology with engineering methodologies, Shah studied the cognitive processes that happen during the engineering design process through design ideation experiments and created cognitive models to help understand the design process [17-19]. The studies combined design (traditional engineering based) and lab (traditional psychology based) experiments focusing at the ideation stage of the design process. Shah's study uses models of information processing from the field of cognitive psychology, human problem solving, mental imagery, and visual thinking. The results are preliminary cognitive models to inform the engineering design process. Shah chose to utilize six ideation components in his study used during the ideation phase of the design process:

1. Provocative Stimuli – ' *the introduction of abstract notions to solve a problem'*

2. Suspended Judgment – ‘ *requesting designers to generate many ideas and requesting designers to generate ideas with the highest quality’*
3. Flexible Representation – ‘ *use of sketches only or use of text only’*
4. Frame of Reference Shifting – ‘ *introduction of new instructions that break the initial problem representation with the objective to solve an alternative simulated problem and obtain insight to solve the initial problem’*
5. Incubation - *‘suspension of conscious problem solving for a specific period of time’*
6. Example Exposure – *‘introduction of well-defined ideas to solve a problem’*

The study exposed groups of students to the six different ideation components and recorded the results of the ideation process. Ideation components were studied individually and also interactions between ideation components were studied. The study group included 237 students divided into two groups then strategically exposed to one or more of the ideation components and the results recorded. During the experiments the students were asked to generate ideas for a specific design task after being exposed to the ideation components. For example, for ideation component ‘Example Exposure’ the students were shown completed examples of the design task before they completed the task. The resulting design ideas were rated based on quantity, quality, novelty, and variety metrics created by Shah. These ideation components, according to Shah, are commonly accepted terms in both engineering design and cognitive psychology fields. Understanding the current limitations of science on internal brain activity Shah combined cognitive psychology with engineering design to create experiments that would reveal a certain amount of important information about design. The study concluded that the implementation of the ideation components had a positive effect on divergent thinking during idea generation. Shah created a framework for linking cognitive psychology theories with engineering design through a cross-disciplinary study using terms common to both fields. Shah's work is important because it demonstrates the need and contributions that can be found by combining disciplines towards a common goal. Shah's work also provides a basis for a different type of design experiment methodology that can lead to metacognitive strategies to aid designers during the design process. This dissertation is different from Shah's work in the methodological approach and design process but similar in searching for a deeper understanding of the cognitive activities of designers.

Williams et al. conducted a protocol study before and after an introductory design course on sophomore mechanical engineering students in order to study the development of design thinking in engineering students [81]. The protocol study included two design sessions where pairs of students were given a design task to complete while being video and audio recorded for data collection. The transcribed verbal text was coded using a FBS (Function, Behavior, and Structure) based coding scheme and checked using inter-coder reliability. William's research results were that design courses focus did correlate with the differences seen in the students design cognition but did not altogether conclude that the design course was the cause of the changes. William's study is important for this dissertation because it provides support for being able to quantitatively measure design cognition.

Howard et al. presents a study that merges the field of engineering design with the field of cognitive psychology but with a focus on the creative process [82]. Howard's research seeks to create a formal creative design process model. Reviews of creativity and engineering design models are presented and a merging of the creative aspects is presented. The creativity models come from the cognitive psychology literature and the engineering design models come from engineering literature. The tools presented by Howard are to aid the engineering designers during the creative process. Howard shows how the creativity process mirrors the beginning stages of the engineering design process which makes for a more cohesive creative design process model.

Ahmed and Christensen conducted an *in situ* protocol study of expert and novice design engineers working in the aerospace field to compare uses of analogical reasoning[83]. This study is important to this dissertation for two reasons (1) the *in situ* method of collecting data is not popular in literature and (2) analogical reasoning is an important part of the cognitive coding scheme presented in this dissertation. The *in situ* method means that the data was collected in the designer's natural setting and in this case the project that the design engineers worked on was assigned by the company where they worked and where the data was collected. Although audio recording devices were used in the study the natural environment appeared more genuine than if a video recording device were present. Although Ahmed and Christensen do not give a detailed account of the actual recording device, it is assumed to be non-intrusive. The study of Ahmed and Christensen concluded that there are differences between the use of analogical reasoning by novice and expert design engineers who participated in the study.

2.5 Documentation Studies in Engineering Design

All designers produce some type of documentation that reveals the development of the design whether on paper, computer models, back of envelope sketches, mind maps, etc. The American Society for Mechanical Engineers (ASME) posts a monthly news article dedicated to asking professional mechanical engineers: *What's inside your engineer's notebook*? Engineers have acknowledged through the ASME site things like:

- "I always have an engineer's notebook with me" (January 23, 2012) [84]
- "I jot down everything from to-do lists to interesting ideas that I pick up when I go to different conferences or seminars" (January 3, 2012) [84]
- "Engineers can't talk without drawing, so if you're sitting having a conversation with someone, you have a way to sketch something out fairly easily" (October 2011) [84]
- "I also keep coding tips and tricks there, as well as documentation of any special cases and special scenarios that I've encountered and that I'm likely to encounter again" (July 2011) [84]

Studying written documentation can reveal many things about the original writer and many famous records have been reviewed and made available to the general public for various reasons. For example Thomas Jefferson's personal letters, Albert Einstein's papers, and Leonardo da Vinci's mirror written notebooks. In order to reveal information about the design process this dissertation will use written design journals under the assumption that if the participants take the time to record text it must be important.

Sobek, in order to find the correlation between thoughts and written documentation during the design process, implemented design journals for a senior capstone design course at Montana State University [30].The students were required to keep the design journals and also received a portion of the course grade for keeping them current. The students were given the journals at the beginning of the semester with the grading requirements for completing entries and keeping the journals current. Each member of the design team was required to keep a journal documenting the process. In three different publications [30-32] Sobek reports the findings, results, and lessons learned from these studies (n= 60 students). Twelve possible coding scheme combinations were created and applied to the design journals to find out what design process variables affect the design outcome. Sobek's study concluded that design process models do not suit novice designers as well as they do expert designers. It was tempting for him to conclude that design process models do not have a place in current engineering curriculum, but further study would be needed to substantiate such a claim. Teaching engineering design process models to novice students who are not as experienced in some engineering fundamentals does look different than teaching expert designers. Although not expounded upon in his study, Sobek noted the importance of the potential cognitive benefits students gain from using a design journal [30, 32]. The main difference between Sobek's study and this dissertation is that our studies will use mixed methods of data collection that will be expanded on in

Chapter 3. Two similar studies conducted by Ekwaro-Osire et al. involving senior design students across their final 2 semesters of a design course [67, 68]. Design journals were given to the students with detailed instructions for recording design activities. The research focused on using student design journals to indicate team participation and also to enhance creativity during the design process. The journals were coded based on a weighted creative design process (in lieu of a traditional coding scheme) with respect to design activity in order to capture and represent the creativity of each student. The weighted creative design process included preparation (10%), innovative opportunity (15%), divergence (25%), incubation (25%), convergence (15%), and evaluation (10%) for a total possible score of 100%. Ekwaro-Osire et al. concluded that creative thought is enhanced when students used design journals. Both Sobek and Ekwaro-Osire et al. highlight the benefits of journal writing and reflective thought during the design process. These benefits include writing about diverse topics, pedagogical benefits, decision making, and increased metacognitive strategies.

Visualizing during the design process can result in many forms of design documentation such as design journals, final reports, presentations, notes, and sketches. These documents can be studied to highlight steps taken during the design process. Westmoreland et al. reviewed Capstone Design Reports visual representations in the form of sketches, CAD drawings, simulations, line drawings, and photographs to find correlations between amount and types of visuals used with course grade [75]. Sketching skills revealed in engineering design documentation have been the topic of several research reports [78, 85-88]. Several advocates exist that promote writing in engineering courses and have research documenting the metacognitive advantages and benefits for students [89-94]. This dissertation will collect data through writings found in engineering design journals to support writing during the engineering design process to alleviate mental loads and aid memory.

2.6 Cognitive Coding Schemes

A cognitive coding scheme is defined as a system developed for the classification of design documentation content for quantitative analysis. Studies of design processes create a record of the designers' activities with as much detail as the study can provide. For example, a protocol may require the designer to talk about what they are doing throughout a design session. Protocol studies may also include an observer who will prompt the designer to speak by asking questions like, "Why did you erase part of your sketch?" The study must output a record describing what the designer did so that it can be analyzed in some fashion. A cognitive coding scheme seeks to provide a lower level of detail about the designers' activities during the design process.

Previous design studies have been published that seek to reveal the cognitive activities of designers [6, 11, 34, 36, 70, 78, 95] . Suwa et al. created a cognitive coding scheme that was applied to a protocol analysis study which revealed the definitiveness of design actions and lead the way for microscopic analysis of design behavior [11]. Another example is freshman cognitive protocol studies which look primarily at first year students design activities and design learning settings. Atman et al. has one such reported study in the book *Design Knowing and Learning: Cognition* *in Design Education* [6]. Atman's paper reviews 4 verbal protocol studies and offers some results and cognitive implications for engineering design education. Fully incorporating the psychology with engineering methodologies, Shah studied the cognitive processes that happen during the engineering design process through design ideation experiments and created cognitive models to help understand the design process [17-19]. The studies combined design (traditional engineering based) and lab (traditional psychology based) experiments focusing at the ideation stage of the design process. Adams created a multidimensional coding scheme that included the following categories: information processing activity, decision activities, step, design cycle, and process [36]. A sample list of basic cognitive activities found from this literature search is shown in Figure 3.

Design Activity Code's	Sobek (2002 Prelim)	Jain/Sobek (2006)	Ekwaro-Osire (2009)	Atman (2007)	Stempfle (2002)	Adams/Atman (1999)	Grenier (2007)
Problem Definition	■	■	■	■			
Project Realization			■	■			
Clarification Strategies					■	■	■
Gathering of Information			■	■		■	
Idea Generation	■	■		■	■		■
Engineering Evaluation	■	■	■	■	■	■	■
Feasibility Analysis				■	■	■	■
Decision				■	■	■	■
Design Refinement	■	■				■	
Project Control					■		■
Planning	■	■			■	■	

Figure 3: Design Behavior Codes

A visual representation coding scheme from Westmoreland et al. is adapted for this work that had previously been applied to final reports from the senior capstone design course [75]. This coding scheme was created to find a correlation between visuals used in the final design report with the grades that the students received. Since some of the codes applied to the visuals were transferrable to the design journals this was a good starting place for the coding scheme. Details about the visual representation coding scheme can be found in the Westmoreland et al. paper from 2011 [75].

The purpose of the design of these research studies for this dissertation was to capture design thinking in the most natural setting for the design without using audio and video recording as was done in previous studies found in literature.

Chapter 3: Methodology- Developing Cognitive Coding Scheme

This chapter presents the detailed development of the cognitive coding scheme. First (Section 3.1), the approach used to create the cognitive coding scheme is presented with references from literature. Second (Section 3.2), the participants are presented and a brief description of their recruitment is given. Third (Section 3.3), the iteration process used to create the cognitive coding scheme is detailed including the involvement of the design journal studies. Also a final version of the cognitive coding scheme is presented. Finally, the verification (Section 3.4) and validation (Section 3.5) steps used for the cognitive coding scheme are presented.

Definitions important for this chapter are cognitive code, cognitive class and cognitive cue. A cognitive code is a design behavior activity that is linked to different design thinking processes. Cognitive class is a group of cognitive codes that is expected to be found together in the design journals. A cognitive cue is text or graphic entry that is found in the design journal that implies design thinking.

3.1 Introduction

Coding schemes are used to quantify and process design thinking research data. Identifying these cognitive activities will improve knowledge about the design process. In Chapter 2 previously published coding schemes are discussed [6, 11, 34, 36, 70, 78, 95]. Coding schemes are developed by researching literature to find common knowledge for a preliminary scheme, applying schemes to data sets, and using previously created schemes. Most of the studies previously published do not present great detail on the development of their coding scheme outside of referencing sources. A good cognitive coding scheme is one suitable for extracting evidence to imply cognitive activities from design documentation. Applications of such a coding scheme could benefit design researchers progress towards developing design competency tools and help clarify the differences between novice and professional design engineers. Previous literature was also used as the initial source for the groundwork of the cognitive coding scheme created for this dissertation. This section describes the detailed literature search and the iterations with the data set used to refine the cognitive coding scheme.

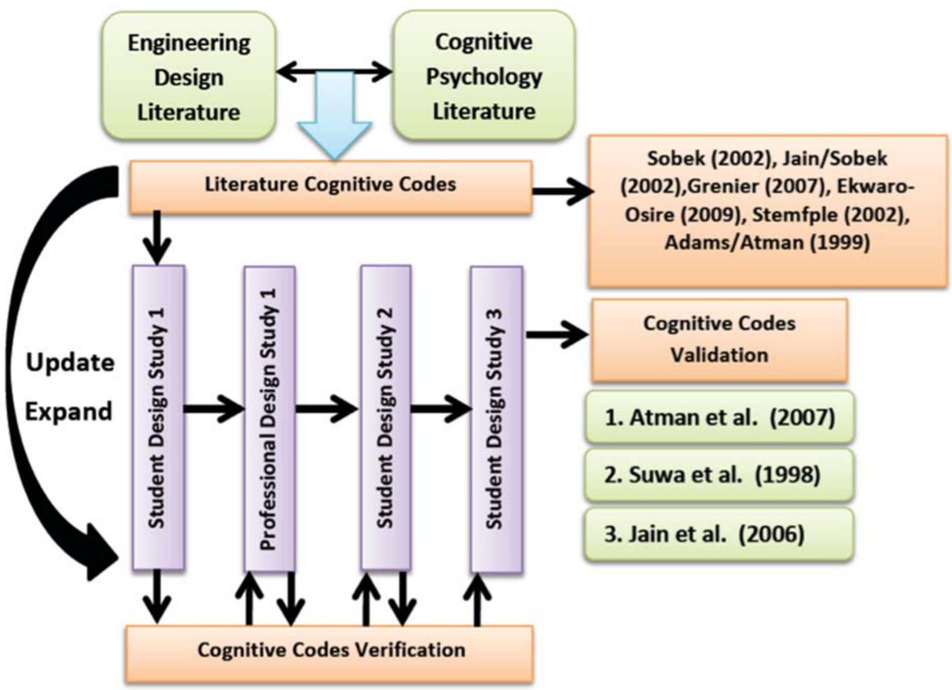


Figure 4: Diagram of Process Used to Create the Cognitive Coding Scheme

A cognitive coding scheme has been developed to reveal insights about design thinking. The coding scheme was created based on the iterative model shown in Figure 4 that should be interpreted in the following order:

1. First engineering design and cognitive psychology literature was reviewed to find out (a) what cognitive operators exist in the psychology literature that can be helpful for to designers and (b) what cognitive coding schemes already exist in engineering design literature.
2. Next a first version of the cognitive coding scheme was created that came from common terms found in the literature.
3. Then four design studies were conducted to collect design thinking data for verification of the cognitive coding scheme. Three studies with students in the senior capstone design course at University of Maryland- College Park. One study was done with professional design documentation loaned to the authors by a former mechanical engineering designer.
4. After applying the codes to the first two student studies and the professional study the cognitive coding scheme was updated and expanded each time. The coding scheme was applied to the first study and then updates were made based on information from the study data. Then the coding scheme was applied to the professional study and then more updates were made based on information from the professional study. Finally the coding scheme was applied to the second student study and then updated again based on that data.
5. The final version of the cognitive coding scheme was applied to the last student study in fall 2011.

6. Finally the cognitive codes were further analyzed and compared with results from three comparable studies found in literature for validation of the cognitive coding scheme. Validation for this dissertation means answering the question: Is the data found from the cognitive coding scheme a true reflection of the design process? In order to asses this we seek to present results that are parallel to other design research.

More details about the studies, the participants, and the subsequent changes made to the coding scheme are given in the following sections in this chapter.

3.2 Study Participants

Students selected as subjects were from three semesters of the Mechanical Engineering Senior Capstone Design course. The studies were done under the management of the author of this dissertation, who was also the course teaching assistant, with the additional guidance of Dr. Linda Schmidt. The design journals collected for these studies as data allowed the researchers to expand and refine the cognitive codes. Assuming that what the designers record in the design journals is significant and relevant to the solution of the design problem is central. The records in the design journal will be used as cues to cognitive activities of the designers. A basic assumption for the study is that in order to record in a design journal some type of thinking has to happen. This leads to the conclusion that the cues are material evidence of design thinking. Moment to moment we can imply thinking from the concrete evidence in the design journals. We are not assuming that every thought has been recorded. Even so, designer patterns in thinking can still be implied from this material external evidence.

As in the Sobek study previously mentioned (Chapter 2 Section 2.6) students in this study were given design journals to use during their lab session, in after-class team meetings or while working alone [30, 32]. Participants in this study recorded their design thoughts in team meetings, during management meetings, during lab classes, in offices, at home, and anywhere at any time that they performed their design work. The design journals gave the students a place to sketch concept drawings, write notes, create lists, record reflections, and document design decisions. The design journal pages were scanned each week using a portable document scanner in the first and second study and also during the final study (Fall 2011) the design journals were signed off on each week of the semester.

The assumption was that when the journal writer recorded something in the journal it has meaning to them at that particular point in the engineering design process. The time during the design process when entries were made is important for the findings of this dissertation. In the student design journal studies, it was requested that each entry include a date. This instruction was included in the design journal guidelines given to the students. Dated design journal entries allow the design segments to be correlated with course due dates for particular assignments as well as particular parts of the design process.

All student participants were given lined and numbered design journals to use during the course of the semester with a one-page design journal guideline to help get them started. These design journal guidelines are shown in the Appendix. Each student was participating on a design team of 4-8 students and had one semester to complete a senior level design project. According to the syllabus each team will "*use the mechanical design process to create a physical artifact to satisfy a particular need*". The student teams follow the product design and development process outlined in Engineering Design, 4th Edition [8]. A sample poster presented at the annual ME Design Day is shown in Figure 5; this is how the design teams present their final design to the university community.

The four design studies shown in Figure 4 were carried out to develop and verify the coding scheme and are described in more detail in the next sections. The aforementioned studies received approval by the University of Maryland under IRB Protocol: 10-0530- Cognitive Design Tasks Study (See Figure 57 and Figure 58 in the Appendix). Under the IRB contract all participants signed consent forms allowing the use of their work for research purposes (See Figure 59 and Figure 60 in the Appendix). Student journaling data was collected over the period of three successive semesters.

Table 1: Study Details

Study Details
Student Design Study 1: Fall 2010 N=15 Duration: 5 Weeks (5) 15 Weeks (10)
Professional Design Study 1: Spring 2011 N=1 Duration: 5 Years
Student Design Study 2: Spring 2011 N=4 Duration: 5 Weeks (4)
Student Design Study 3: Fall 2011 N=9 Duration: 15 Weeks (9)

3.2.1 Student Design Study 1

In the fall semester of 2010 a pilot study was conducted with students (N = 15) from the Mechanical Engineering Senior Capstone Design course (ENME 472). The students in this study were split into two smaller groups, one called *Team Study (n=10)* and one called *Individual Study (n=5)* including students from the different sections of ENME 472 course. Each student in the *Individual Study* was from a different design team working on a different project.

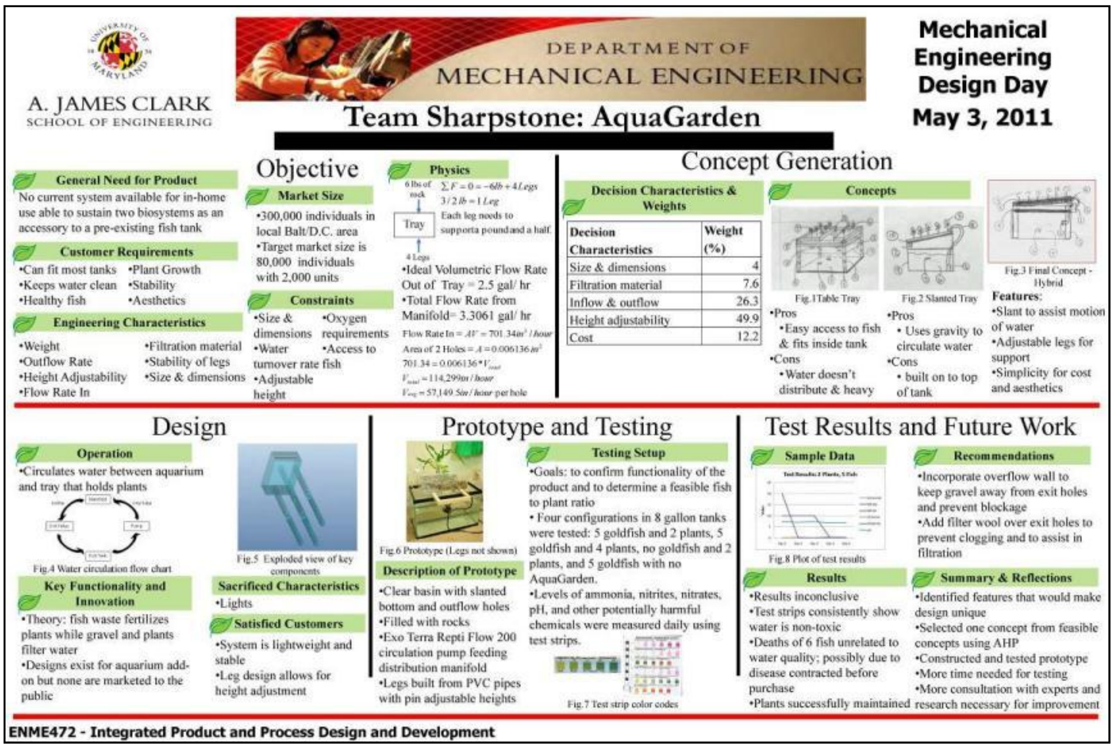


Figure 5: ME Design Day Poster Sample

The students in the *Individual Study* were solicited to volunteer through e-mails from the author of this dissertation who was at the time the ENME 472 teaching assistant. The e-mail simply stated:

Hi 472 Students,
I am looking for 5 volunteers to participate in a small study using design journals during the mechanical engineering design class. In this study participants will record information in a design journal (that I will provide) and compensation is available for participants. This is a small pilot study that I am doing for research towards my PhD in Mechanical Engineering."

Figure 6: Recruitment E-mail for Student Design Study 1

The data collection details for Student Design Study 1 are summarized in Table 2. *Team Study* students were required to keep a design journal for 5% of their ENME 472 course grade per the instructor guidelines (Dr. Linda Schmidt was their instructor). Students in the *Individual Study* participated as volunteers.

Table 2: Student Design Study 1 Context

Student Design Study 1 Details	
Study Time	Fall 2010
Participants	N= 15 students in two groups • *Team Study*: 10 students (course required participation) • *Individual Study*: 5 students (volunteer participation)
Motivation	• *Team Study*: The satisfactory completion of the journal was a course requirement worth 5% of the total grade. The journal pages were scanned periodically and students were be given feedback as to their adequacy. • *Individual Study*: Students who successfully completed the study were provided with a gift card to a local establishment, i.e. the campus bookstore.
Context	Students enrolled in mechanical engineering senior capstone design
Data Collection Period	• Team Study: During entire semester • Individual Study: Used design journals during concept generation phase of their course only
Journal Entry Oversight	No formal oversight

The *Team Study* group included 10 students working in 2 teams on 2 separate projects. The section was unique in that 5 students participated in the course through videoconferencing from the Southern Maryland Higher Education Center (SMHEC). These remote students were interns at the Patuxent River Naval Air Station Aircraft Division (NAWCAD) who were the first cohort of students to participate in a program that involves distance learning for many of the Junior- and Senior-level courses. Each capstone design team was made up of a mix of on-campus and remote students. The projects were sponsored by NAWCAD personnel. All students in Dr. Schmidt's section participated in the study for the entire semester. The students in this section were given specific Design Journal Guidelines on filling out the journal shown in Figure 61 of the Appendix.

The *Individual Study* group consisted of 5 volunteer students from the 3 traditional sections of the course. *Individual Study* students did not receive course credit for their participation. The Design Journal Guidelines given to the students in the Individual Study were the same except the compensation section read "Student who successfully completes this study will be provided with a gift card to a local establishment, i.e. the campus bookstore". (Reference Figure 62 of the Appendix) Students in the *Individual Study* were notified of all the guidelines of the study including a recorded exit interview at the completion of the study. The duration of the *Individual Study* was 6 to 8 weeks, depending on when they first received their design journals. The original intent of this time-restricted study was to capture design documentation during the entire concept generation period in the design process.

Design journals were collected from the students in both studies, at the end of the semester for the *Team Study* and at the end of 8 weeks for the *Individual Study*. The students in the *Individual Study* were contacted within 2 weeks after completing the study to participate in the exit interview.

3.2.2 Student Design Study 2

In the spring semester of 2011 a second design journal study was conducted with students (N = 4) from the Mechanical Engineering Senior Capstone Design course (ENME 472). The students in this study were split between two teams, with 2 students working on one project and 2 students working on a different project. All students in this study were from the same section of ENME 472 which was being co-taught by Dr. Linda Schmidt and the author of this dissertation. The students were all volunteers in this study. Volunteers were recruited by e-mails sent through the teaching assistant and also by announcements made during the student's lab sections.

The e-mail simply stated:

Hi Teams in Section 0101,
Myself (TA-Nikki) and Dr. Schmidt are looking for 10 volunteers to participate in a short 5-week team design journal study that will start Tuesday March 8th through Friday April 8th. We are asking students to keep design journals for short periods of time during the design process in order to gain a more in-depth understanding of the different aspects of mechanical design. This is a short pilot study. Participants will be compensated for their time and efforts towards the study with a $30 gift card to Barnes and Nobles. Please reply to me via e-mail at snwest@umd.edu if you would like to participate. Design Journals will be distributed on Tuesday so please reply to me before our lab section. We are only looking for 10 volunteers.

Figure 7: Recruitment E-mail for Student Design Study 2

The data collection details for Student Design Study 2 are summarized in Table 3.

Table 3: Student Design Study 2 Context

Student Design Study 2 Details	
Study Time	Spring 2011
Participants	N= 4 students in two groups (course assigned groups, not chosen for this study) Individual Study: 4 students (volunteer participation)
Motivation	Students who *successfully* complete the study will be provided with a $30 gift card to a local establishment, i.e. the campus bookstore.
Context	Students enrolled in mechanical engineering senior capstone design
Data Collection Period	5 weeks- began on March 8, 2011 and ended on April 8, 2011.
Journal Entry Oversight	The journals were reviewed each week by the researcher to ensure entries had been made and answer any questions the students may have had.

This study introduced the Smartpen technology with the journal recording. The Smartpen technology *Livescribe* allows the students to capture audio and text through the pen device and sync together for future review. The product promotes a

"Never Miss a Word" Smartpen device. The Smartpen features an infrared camera, built in speaker, microphone, audio jack, USB connector, and OLED display. One student on each team in this study was given the Smartpen technology with up to 200 hours of recording capability and 2GB of memory. Included with the pen is the software required to sync the recorded design sessions on the computer and create movies to share with other team members. Also included is a lined design journal with 50 front and back pages especially suited for use with the Smartpen technology. Figure 8 shows the Smartpen technology including labels for the main components.

Figure 8: Smartpen Technology [96]

This technology was chosen because it uniquely joins new technology with traditional paper and pen style of recording. Engineering students live in a technology driven society and the design of this product is meant to promote recording by hand without the fear of missing information simply because you cannot transcribe fast enough. It was assumed that this technology would promote interest in keeping a design journal. The 2 students using the Smartpen technology were given an additional waiver to sign because of the costs involved with acquiring the pens and to ensure future uses of the technology. This simple agreement is shown in Figure 64 in the Appendix.

The experimental design required that one student from each team was asked to use the Smartpen technology. The other 2 students in this study were given the traditional design journal to record during the semester. Both participants each received a lined design journal with 96 front and back numbered pages. The duration of this study was 5 weeks, from March 8, 2011 to April 8, 2011. The intent of this time restricted study was to capture design documentation from right after the concept generation process leading into the embodiment design part of the design process.

The study was managed in a similar way to the pilot study. Journals were checked every week to ensure that the students were actually using them and also to correct any issues acclimating with the new technology for the Smartpen users. The students in this section were given specific Design Journal Guidelines on filling out the journal shown in Figure 63 of the Appendix. All the students in this study completed exit surveys and returned them to the author via e-mail after the end of the semester. Design journals and Smartens were collected from the students in both groups at the end of the 5-week period during the week of April 8, 2011.

3.2.3 Student Design Study 3

The final design journal study was done in the fall 2011 semester with the students in the Mechanical Engineering Senior Design course (ENME 472). The authors decided that in order to capture the full picture of the design process as apparent in the professionals design journal the students would need to use the design journals for the entire semester.

Motivating the students in student design study 1 and 2 to actually complete their journals was a challenge and is something that the authors addressed for student design study 3. In order to capture the design journals in a more natural setting it is not favored to pressure the students or micromanage the journaling process because that would compromise the data. Strategies were implemented that encouraged the students to use the journals such as a strict review and feedback policy. If the students know that the journals will be reviewed on a certain day each week and detailed feedback given then they may be more inclined to engage in the journaling activity.

After learning from the previous studies best practices were gathered for acquiring volunteers and monitoring the plan for this study was created. The students who volunteered for the study were given both the protocol information and also the Design Journal Guidelines shown in Figure 65 in the Appendix. In order to get a high number of participants for the study volunteers were solicited during the very first lecture of the semester for the course. A short presentation was created that detailed the design journal study, the benefits of using a design journal, and how the study correlated with the goals for the senior design course. The slides from this presentation are shown in the Appendix in Figure 66 and Figure 67. No e-mails were sent for solicitations because all the students heard about the study during the first course lecture. The data collection details for Student Design Study 3 are summarized in Table 4.

This design study was administered over the entire fall 2011 semester that is 15 weeks. Students who were interested in volunteering to participate in the study were given the design journals during the first course lecture.

Table 4: Student Design Study 3 Context

Student Design Study 3 Details	
Study Time	Fall 2011
Objective	As students are participating in their Capstone Senior Design Project we want to introduce design journals as a design documentation method and study the content and students attitudes towards using design journals. During this investigation we seek to answer the question: "What can engineering documentation reveal about cognitive sequences or patterns that exist?"
Participants	N= 15 students in nine groups (course assigned groups, not chosen for this study) Individual Study: 15 students (volunteer participation)
Motivation	Students who consistently record in the design journals were compensated every 5 weeks with a $20 Gift Card to Barnes and Noble that was delivered electronically to their e-mail address for a total of $60 for all semester participation.
Context	Students enrolled in mechanical engineering senior capstone design from nine groups with projects ranging from solar powered tents to harvesting energy from walking systems.
Data Collection Period	15 weeks
Journal Entry Oversight	The design journals will be checked weekly by the researcher and signed to monitor student participation. This is to ensure that the students are actually using the journals and not waiting until the end of the semester to make entries.
Administration	The study is best administered an integrated part of the course assignments. The researchers are able to give an introduction to the study during the first class lecture. The design journals should be given to the students during the first lab period, immediately after teams have been formed.

Although the goal was to have 20 students participating in the study, only 15 volunteered and, of those 15, 9 participated throughout the entire fall 2011 semester. It was actually expected that some of the students would drop out of the design journal study because of other obligations that burden students at the final stages of their undergraduate careers. The students who did not complete the study were still asked to fill out the exit survey for their short participation in the design journal study.

The students in the senior design course meet for lab once per week and during this time each week the design journals were checked by signing and dating the final entry to ensure that the students were actually recording in the design journals. Each week the journals were checked and signed by the author of this dissertation. Throughout the semester the students were sent emails to remind them to record in the design journals and also to answer any questions that they may have during the study. On occasion a student may have forgotten to bring their design journal to lab then it would be checked during the following week's lab period. Also when the journals were checked short notes were taken by the researcher to provide adequate feedback to the students when necessary. Since dating of the journal entries is important to correlate them with important course due dates students were also gently reminded weekly to date their records. The content of the entries was left entirely up to the students giving them control of how they would utilize the journals for their benefit during the design course. Students who participated in the design journal study the entire semester also completed exit surveys that they submitted to the teaching assistant through e-mail. The design journals were collected from the students at the end of the semester on December 13, 2011.

3.2.4 Professional Design Study 1

The goal of learning a craft is to become proficient. Comparing the students' design journals with one done by a professional design engineer will delineate the differences. A professional design journaler was sought as part of the data collection for this dissertation. His official job title during the time when the journals were recorded was research engineer. He was trained as a mechanical engineer at a large public university in the northeast. His career spans some 30 years in the field of engineering. The complete project, funded by NASA, was a satellite launched into space by a rocket in 1996. He was responsible for designing everything mechanical on the project. He was working on a global team of engineers, scientists, and other project managers.

He previously worked for the government on a space related mechanical engineering design project and permitted the author to also include his design journals in this research. He created 3 design journals for this 1 project that he worked on for 5 years. The professional designer was not asked to create these design journals; this was something that he was accustomed to doing for his design projects. His journals were acquired after he created them in order to make comparisons with the student's journals and also to help with the refinement of the coding scheme. Due to the nature of the work and the agreement with the researchers the content of the journals will not be published.

The professional design engineer also participated in a video recorded exit interview about the design journal that he created. This interview was transcribed and details will be given in Chapter 6. The data collection details for Professional Design Study 1 are summarized in Table 5.

Table 5: Professional Design Study 1 Context

Professional Design Study 1 Details	
Study Time	Summer 2011
Participants	N= 1 professional engineer

Motivation	None
Context	Government contractor working on a design project
Data Collection Period	May 1, 1991 to November 22, 1996

3.3 Creation of the Initial Coding Scheme

Quantifying any data that we found in the design journals required the formation of a comprehensive coding scheme. The process of creating the cognitive coding scheme started with sifting through a mass of literature related to cognitive activities of designers (particularly engineering designers) to create a thorough list of cognitive activities. Previous studies were not limited to design journal research because other protocol studies offer insights into cognitive processes that can be applied to this dissertation. A more comprehensive survey of these previously done research studies can be seen in Table 6, these are also general references to coding terms adapted for this research.

Table 6: Cognitive Processes Literature Review

Cognitive Processes from Literature	
Author	***Research Summary***
Grenier et al. [78]	Coded design journal sketches and text and also identified which individual student did the work. 2 Teams, McGown [87] Sketch Levels, and Stempfle [70] codes used. (Goal Clarification, Idea Generation, Analysis, Decisions, and Project Control)
Ball et al. [34]	Coded student verbal texts from interviews and also coded student diaries that were done according to the format given by the instructor. (Goal, Solution Idea, Planned Method, Constraint, Decision Method Used, and Comments)
Suwa et al. [11]	Coded video/audio recording and hand sketches. Video/audio was segmented for coding. Subject was asked questions following while watching a video of the design session. (Physical, Perceptual, Functional, and Conceptual)
Adams et al. [6, 36, 71]	A 5 dimensional coding scheme was created based on the following categories: information processing activity, decision activities, step, design cycle, and process. Cognitive processes and activities were broken into three types: cognitive processes, cognitive triggers, and cognitive decisions. (Define, Specify, Integrate, Clarify, Organize, Search, Conceptualize, Evaluate, Assess, Examine, Capture, Modify, Plan, and Monitor)

Various terms from literature were collected and merged into a list of cognitive activities commonly found among researchers in this area. Missing from the literature were commonly accepted terms for the types of cognitive activities that occur during design thinking. Uniformity in the terms used was sought by comparing the researcher's definitions of various cognitive indicators. Even though common terminology is missing, the terms from literature were grouped into categories based on previous researcher intention. These terms were not used everywhere with identical language but in many cases the context was the same. For example Adams defines problem clarification strategies as "Examination of information to understand or interpret the nature of the problem" [36] and Grenier defined problem clarification strategies as "communicative acts dealing with the goal space" [78] and both were interpreted as similar definitions of "goal clarification" which is shown in the cognitive code table as such. Sifting through the terms and creating a spreadsheet with the different cognitive activities identified by the researchers gave us the breadth of the literature that was before us. Finding commonality between the meanings and intent of the cognitive activities was a challenging task. This required the author to presume in certain cases the meaning of terms that were not explicitly defined in literature. The first version of the cognitive section of the coding scheme is shown in Table 7.

The cognitive codes presented in Table 7 represent the most common terms categorized from literature. An example Solution Generation statement is "Go home and make 3 designs before the next team meeting". An example Goal Clarification statement is "What is our goal?" An example of Artifact Analysis is "What are the forces on the object?" This first coding scheme was to be applied to a set of data to start the verification process. More details about the verification steps are described in the next section.

Table 7: First Version of Coding Scheme

Cognitive Coding Scheme Draft Version			
Cognitive Code	***Cognitive Cue***	***Definition***	***Reference***
Goal Clarification	Objectives, (customer) requirements, information gathering	Explaining the objective of the design project	[34, 36, 70, 71, 78]
Solution Generation	Project variation and selection, options/ideas considering, sketches, concepts	Production or creation of solutions to the design project	[34, 36, 70, 71, 78, 97]
Artifact Analysis	Questioning: how much? questioning involving math, physics, and free body diagrams	Inspection of artifact and components including mathematical reasoning	[44, 70, 78, 97]
Artifact Evaluation	Questioning: how well? design process or progress related questions	Assessment of design process stages	[36, 44, 70, 71, 78, 97, 98]
Artifact Decision	Finalizing design ideas	A choice made during the design project	[34, 36, 70, 71, 78, 97]
Content Control	Verifying final design specifications, controlling variables during design testing	Managing variables related to the design project	[34, 70, 78]
Assumptions	Assuming parameters, constraints	Making statements or guesses related to constraints needed for the design project	[97]
Analogical Reasoning	Use of words "like", "similar", "as" to relate by use of analogy	Showing similarities and likeness between two objects	[44, 95]
Explanation	To establish action by reasoning	Clarification of something	[97]
Self-Reflection	Thoughts, personal writings, inner revelations, evidence of time spent in thought	Contemplation about the design product and the design process	[36, 71]

3.4 Verification

As indicated in the model (Figure 4) the first coding scheme (Table 7) was applied to the data from Student Design Study 1 and thereafter changes were made to the cognitive coding scheme based on what the data revealed. This section will detail the changes made to the first version of the cognitive coding scheme after it was applied to Student Design Study 1 & 2 and Professional Design Study 1. The application of the coding scheme details have been dedicated to Chapter 4.

3.4.1 Student Design Study 1

The first version of the coding scheme shown in the previous section was applied to the student design journals from Student Design Study 1 for the first step in the verification process. Some items in the cognitive coding scheme were noted as needing a change but were not actually changed until after looking at the professionals first design journal.

3.4.2 Professional Design Study- Journal 1

The professional design journals (3) were coded in 2 steps- journal 1 was coded with the original coding scheme (Table 7) and then changes were made to the coding scheme and then journal 2 and 3 were coded with the revised version of the coding scheme. This section will discuss the changes made after the coding of journal 1. These changes were made because new types of records were found in professional design study journal 1 and the student design study 1 journals. The professional design study journal 1 was coded on site over a period of 1 week using the first version of the scheme shown in Table 7.

During the coding process notations were made. Those later revealed the changes that needed to be made to the coding scheme. The major changes made after the professional design study journal 1 and student design study 1 were coded are shown in Table 8.

As seen in the table original codes were expanded to be more specific rather than just design process related. The revisions described in the table were done because the coding scheme was not presenting the level of detail that the researchers were looking for. According to what was found in the first design journals, the coding scheme was expanded to include more cognitive codes. This was done after the coding of professional design study journal 1. The project management codes were added because the professional engineer included a wider variety of cognitive activities than student design study 1. The professional engineer also included many cross-references and personal record keeping notes.

Table 8: Changes Made to the Coding Scheme after Professional Design Study Journal 1 and Students Design Study 1

First Round of Changes Made to the Coding Scheme	
Changes Made (Added Codes)	***Definition/Cue***
1. Search	Split out from Goal Clarification
2. Customer Requirements	Split out from Goal Clarification
3. Problem Statement Clarification	Split out from Goal Clarification
4. Project Ideas	Split out from Solution Generation
5. References	Split out from Solution Generation
6. Material Options	Split out from Solution Generation
7. Estimates	Split out from Solution Generation
10. Calculations	Split out from Artifact Analysis
11. Questioning	Split out from Artifact Analysis
12. Testing Procedures	Split out from Content Control
13. Variables	Split out from Content Control
14. Recommendations	Split out from what was found in Other
15. Conclusions/Results	Split out from Decisions
16. Explanations	Split out from Decisions
17. Criteria List	Split out from Decisions
18. Design Changes	Split out from Decisions
19. Personal Notes	Split out from Self Reflection
20. Design Process Notes	Split out from Artifact Evaluation
21. To Do Lists	Split out from Self Reflection
22. Revelations	Split out from Self Reflection
23. Meeting Notes	Split out from what was found in Other
24. Task Assignments	Split out from what was found in Other

25. Acquired Items	Split out from what was found in Other
26. Price Quotes	Split out from what was found in Other
27. Task Completion	Split out from what was found in Other
28. Project Milestones	Split out from what was found in Other
29. Field Trip Notes	Split out from what was found in Other
30. Mistakes	Added from what was found in professional design study journal 1
31. Cross References	Added from what was found in professional design study journal 1
32. Design Revisions	Added from what was found in professional design study journal 1
33. Illegible Entries	Added from what was found in professional design study journal 1
34. Designer Signature	Added from what was found in professional design study journal 1

The main change that was made to at this step was to tease out some more cognitive codes from the cognitive cues that we found in the design journals. For example goal clarification was broken down into search, customer requirements, and problem statement clarification. Another example is that self-reflection code was changed to personal notes, design process notes, to do lists, and revelations.

One of the reasons for adding the additional codes found in Table 8 was because a high number of the design segments were coded as "none" meaning that the previous codes did not apply. It was surprising that the "none" category was higher than any other coding category using the first version of the coding scheme from Table 7. The professional's journals were immediately found to be rich with details and information that was not found in the student's journals. The cognitive part of the coding scheme was expanded to include 33 cognitive codes.

3.4.3 Professional Design Study- Journal 2 & 3

The second version of the cognitive coding scheme was applied to the professional design study journals 2 &3 for further verification. This version of the coding scheme had 35 detailed cognitive codes. Also the professional design study journal 1 was re-coded using the newer version of the coding scheme so that the professional data would be uniform. The professional design study journal 1 was coded on site over a period of 1 week. The minor change made after the professional design study journal 2 &3 were coded is shown in Table 9.

Table 9: Changes Made to the Coding Scheme after Professional Design Study Journal 2&3

Second Round of Changes Made to the Coding Scheme	
Changes Made (Removed Code)	***Definition/Cue***
32. Design Revisions	Merged with Design Changes

After coding professional design journals 2 & 3 we found 2 codes that meant the same thing but used different words: design changes and design revisions. One of the codes was removed. This was done after professional design study 1. These similarities caught the researcher's attention as something that needed to be captured to increase our understanding of the design process.

3.4.4 Student Design Study 2

The third version of the cognitive coding scheme was applied to the student design study 2 journals for further verification. This version of the coding scheme had 34 detailed cognitive codes. The minor change made after the student design study 2 journals were coded is shown in Table 10.

Table 10: Changes Made to the Coding Scheme after Student Design Study 2

Third Round of Changes Made to the Coding Scheme	
Changes Made	***Definition/Cue***
Code Added	
36. Definitions	Added because found in students journals
37. Engineering Characteristics	Added to show course instructor influence

The codes shown in Table 10 are related to the specific design instruction given in the ENME 472 course. This reveals the influence that a design course has on the design process.

3.4.5 Final Cognitive Coding Scheme

Throughout the process of creating the cognitive coding scheme each change had to be rationalized according to story that the data told. Changes made to the coding scheme are outlined in the previous sections. The changes shown above were warranted due to the records found in subsequent design journals. The final version of the coding scheme to date is shown in Table 11. This final version of the coding scheme was applied to the student design study 3 journals that were conducted in the fall 2011 semester. We now have confidence that our coding scheme is useful for revealing the cognitive activities that occur during the design process. The final coding scheme will allow for comparisons between the students and the professionals level and patterns of design thinking at different stages of the design process.

The cognitive codes shown in Table 11 were grouped into “coding classes” according to similarities in the type of cognitive activity described by the code. The coding classes are information seeking and noting, problem understanding, idea generation, analysis, decisions, project management, reflection, and other. It is important to note that there are items recorded in the design journal that have no significance to design thinking and that is what comprises the "other" cognitive class. These classes will be useful in finding some relationships between occurrences of codes in one journal and the comparison of occurrences between journals.

Table 11: Final Cognitive Coding Scheme Including Class Definitions

Cognitive Code	Cognitive Cue
1. Information Seeking and Noting – searching, framing, and marking instances for collecting information that will support the development of a solution to the design problem. This also includes records of inquiries made or needed in reference to the design problem or process.	
1. Search	Looking for information relating to the design project at any stage of the design process
5. References	Source of information such as books, blogs, person, tables, and charts that needs to be available for future reference
11. Questioning	Requesting information about the project that is not at the time known, usually ending statements with a question mark
26. Price Quotes	An estimate from a vendor or company related to the price of products or services
36. Definitions	Meaning of a word.
2. Problem Understanding- an interpretation of the nature of the design problem	
2. Customer Requirements	Describing the product requirements from the perspective of the customer
3. Problem Statement Clarification	Making the problem statement clearer by explaining it in greater detail
17. Criteria Lists	List of things that must be considered when making a decision or judgment about the project
37. Engineering Characteristics	A solution-neutral way of describing the customer requirements.
3. Idea Generation- creating, sketching, outlining, and selecting various solutions or solution parts to the design problem.	
4. Project Ideas	Variations of the project ideas for selection, different options considering, and project concepts
8. Analogical Reasoning	Use of words "like", "similar", "as", etc. Using text or visuals to compare components of the project
6. Material Options	Choices of materials to use for the project
4. Analysis- systematic examination or separation of the problem components into individual parts order to understand it or draw conclusions from it	
7. Estimates	Rough assessments of various parts of the project
9. Assumptions	Suppositions made and accepted to be true without prior confirmation
10. Calculations	Involving math, physics, and free body diagrams. Number and formulas used with mathematical operators
12. Testing Procedures	Establishing testing specifications and methods for the project
13. Variables	Project components that is liable to change before the project is completed
16. Explanations	To establish by reasoning
5. Decisions- conclusions and alterations made to the design, including recommendations from outside sources	
14. Recommendations	Suggestion to what is a good or beneficial thing to do for the project

Cognitive Code	Cognitive Cue
15. Conclusions	The outcome of some action or the outcome of the project. A decision made after some analysis for the design project
18. Design Changes	A difference in the design from a previous version of the design
6. Project Management- statements related to organization of the design project, including (but not limited to) team members and budget constraints	
21.To Do Lists	A list of items that need to be completed for the project by the journal writer or by others associated to the team
23. Meeting Notes	An unofficial record of what is said or done during a meeting
24. Task Assignment	Something given to the journal writer to complete by someone else who chose them to do it
25. Inventory	Things obtained for the project such as computer programs, materials, and other parts
27. Task Completion	Recording the act of completing something for the project
28. Project Milestones	Significant dates and accomplishments in the history of the project
29. Field Trip Notes	Notes about a trip to any place related to the project and how it is related to the project
7. Reflection- turning one's thoughts back, especially the process of reconsidering previous actions, events, or decisions	
19. Personal Notes	Informal notes about various parts of the project including feelings about the design
20. Design Process Notes	Related to how well the design artifact is progressing in the stages of the design process
22.Revelations	A new thought or idea about the project that was not previously known
30. Mistakes	Recorded error made in the design journal
31. Cross References	Notation directing the writer or reader of the design journal to look elsewhere for more details or updated design notes
8. Other – none of the other classes apply	
33. Illegible Entries	Journal entry that is not legible and therefore not able to be coded
34. Designer Signature	Designers name signed in the journal entry
35. No Evidence of Cognitive Activity	No clear evidence of the cognitive process from the given text or pictures. This includes titles, lists, assigned tasks, paper review, report outlines, poster outlines, professor comments, etc.

3.5 Validation

Coding schemes present in literature are varied by content and by what they are trying to reveal about the design process. For example some coding schemes are created for design activities that only occur during the conceptual design part of the design process. Studies comparable to this work are (1) a design activity study done by Atman [4], (2) a design process study done by Jain and Sobek [29], and (3) work done to reveal cognitive behavior patterns by Suwa et al. [11]. In order to show that the proposed coding scheme is comparable to others found in literature, this section will show that the scheme can be as successfully used as the other code sets.

3.5.1 Atman et al. (2007)

Atman et al. (2007) present a study comparing students (freshman and seniors) to experts. The experiment involved "*real world*" professional design engineers in order to appropriately target design-learning outcomes. Atman et al. used a verbal protocol method while the participants designed a playground, then the transcripts were segmented, time stamped from the protocol's video and audio recording, and coded. The coding scheme applied to the transcripts was based on a composite of general models of the engineering design process developed by Atman [99]. The model that she presented in the paper was developed from her experience with freshmen course design texts.

It is important to note the differences in execution of the Atman et al. study and the study done for this dissertation.

- Atman et al. [4] participants designed a playground for children. Student Design Study 3 students were all seniors and participated on different teams in a capstone design course. They created projects such as eco-powered tents and automatic house door locking systems. The expert in Professional Design Study 1 worked on the mechanical and electrical components on a space mechanism.
- Atman et al. [4] used a timed playground design activity that only lasted 3 hours and the students in Student Design Study 3 recorded in their design

journals for 15 weeks. Professional Design Study 1 lasted 5 years. The coded segments in the Atman et al. paper were time stamped because the verbal protocol process utilized actual live audio recording.

- Atman et al. [4] analyzed the verbal protocol data from both the students and the professional in her study. Student Design Study 3 and Professional Design Study 1 recorded the design process in written journals.
- Atman et al. [4] used 19 experts, 26 freshmen, and 24 seniors in her study. Student Design Study 3 used 9 students and Professional Design Study 1 used 1 expert.

Major classes declared in the Atman et al. coding scheme are problem definition, gather information, generate ideas, modeling, feasibility analysis, evaluation, decision, communication, and other. Atman's design activity codes are comparable to some of the codes from this dissertation's cognitive coding scheme. The comparable codes for the proposed coding scheme are shown in Table 12. These groups of cognitive codes are used to compare the results from this study with the study done by Atman et al. [4]. It's not surprising that this dissertation's cognitive coding scheme has many codes that don't apply because of the difference in durations of the design activities. Atman's codes were applied to a timed design activity and the coding scheme that is in this dissertation can be applied to design problems that are solved over a longer period of time, like months or years.

Table 13 shows selected design activity results from the Atman et al. paper's design study [4]. These results are matched with results that are similar to the coding scheme in this dissertation.

Table 12: Comparing Coding Schemes: Atman et al. [4] and this Dissertation

Comparison of Atman et al. Study Codes to Proposed Cognitive Coding Scheme	
Atman et al. Design Activity Coding Scheme	Cognitive Codes
Problem Definition (A1)- "*defining what the problem really is"*	Customer Requirements (2), Problem Statement Clarification (3), Criteria Lists (17)
Gathering Information (A2)- "*searching for and collecting information (i.e., facts, data) needed to solve the problem*"	Search (1), Questioning (11), Assumptions (9), Definitions (36)
Generating Ideas (A3)- "*thinking up potential solutions (or parts of potential solutions) to the problem"*	Project Ideas (4), Analogical Reasoning (8)
Modeling (A4) – "*detailing how to build the solutions (or parts of the solution) to the problem. Applies to initial solution concepts as well as the final design"*	Estimates (7), Calculations (10), Variables (13)
Feasibility Analysis (A5)- "*assessing and passing judgment on a possible or planned solution to the problem (or parts of the problem)"*	Engineering Characteristics (37)
Evaluation (A6)- "*comparing and contrasting two (or more) solutions to the problem on a particular dimension (or set of dimensions) such as strength or cost"*	Testing Procedure (12), Material Options (6), Explanations (16)
Decision (A7)- "*selecting one idea or solution to the problem (or parts of the problem) from among those considered"*	Recommendations (14), Conclusions/Results (15), Design Changes (18), Mistakes (30)
Communication (A8)- "*communicating elements of the design in writing (e.g., sketches, diagrams, lists, and reports), or with oral reports to parties such as contractors and the community"*	References (5), Personal Notes (19), Design Process Notes (20), Acquired Items (25) Project Milestones (28), Cross References (31) Task Assignment (24), To Do Lists (21)
Other (A9)- "*none of the above codes apply"*	Revelations (22), Illegible Entry (33), Designer Signature (34), Other/No Evidence of Cognitive Activity (35), Meeting Notes (23), Price Quotes (26), Task Completion (27) Field Trip Notes (29)

The comparisons in Table 13 are not only more evidence that the coding scheme can collect similar information but also that in some cases (result 2 and 3) the results are in agreement. Recall that the studies' methodologies were different and the design projects and time durations were also different. The Student Design Study 3 codes related to a project that lasted 15 weeks, much longer than the 3-hour playground design task.

Table 13: Comparison with Atman et al. 2007 [4] Paper

Findings from the Atman et al. Design Study Compared to Proposed Cognitive Coding Scheme Findings	
Atman et al. Result From transcripts of think aloud protocols	*Student Design Study 3 (SDS3) and Professional Design Study 1(PDS) Comparable Results*
1. *"Experts spent more time in the problem scoping stage including problem definition (A1) and information gathering (A2)"*	1. The expert recorded 4% entries in the problem scoping stage and the students recorded 11%
2. *"Experts spent more time in the project realization stage including decision (A7) and communication (A8) activity"*	2. The expert recorded 34% entries in the project realization stage and the students recorded 23%
3. *"Experts spent more time on the overall design problem"*	3. The expert recorded 95% more design sessions than the students
4. *"Experts had significantly more coded objects than the students"*	4. The expert recorded 98% more design segments than the students
5. *"Experts and students did not have a significant difference in number of total transitions (design activity and design phase transitions)"*	5. The expert transitioned 96% more between design activities (A1- A9) than the students The expert transitions 73% more between design phases than the students

The numbers in the right hand column from the proposed cognitive coding scheme do not agree with Atman's conclusions in the case of findings 1, 4, and 5. This is not surprising because the professional was working on a much more complex project, than the students' capstone design projects. If the subjects were working on the same design problem we might expect that similar results to Atman's. Nevertheless, this validation exercise shows that this dissertation's coding scheme can collect similar information to the one used by Atman and even more detailed design process information.

3.5.2 Jain and Sobek (2006)

Jain and Sobek (2006) conducted a design journal study with senior capstone design students at Montana State University [29]. The design journals were used *in situ* during the 15-week capstone design course, similar to how journals were used with the students in Student Design Study 3. The Jain and Sobek students recorded 47 design journals across 14 design projects. There were differences between the two studies.

- The Jain and Sobek students' projects come from industry with a written needs statement; the students in Student Design Study 3 come up with their own project ideas and must define their own customers and identify the needs of those customers.
- The Jain and Sobek students work on teams of two to four students and the Student Design Study 3 teams range from five to seven.
- The Jain and Sobek students received 15% of their course grade for the design journal. The Student Design Study 3 students were all volunteers receiving a $20 gift certificate after periods of journaling.
- Hence the Jain and Sobek student's journals were periodically graded with a pre-determined rubric. The students in the Jain and Sobek study were monitored more closely than the students in Student Design Study 3 and the students were more consistent with time and date stamping entries in their design journals. The Student Design Study 3 design journals were checked weekly but not for content just to ensure the students were consistently using the journals. The Student Design Study 3 journals were also signed each week and blank spaces were crossed out.

The coding scheme created by Jain and Sobek is actually a coding matrix shown in Table 14. This matrix based coding scheme allowed for each design activity to receive 2 codes. One code describes the design activity. The other code is the concept, system, or detail level of design that the entry refers to. Jain and Sobek also coded for project management, report writing, and presentation preparation but did not use those results for analysis in the cited publication.

Table 14: Coding Scheme from Jain and Sobek 2006 [29]

Jain and Sobek Coding Matrix

Design Activities	Concept	System	Detail
Problem Definition	C/PD	S/PD	D/PD
Idea Generation	C/IG	S/IG	D/IG
Engineering Analysis	C/EA	S/EA	D/EA
Design Refinement	C/DR	S/DR	D/DR

Included in the journal coding identification process for this dissertation is a classification for design phase. The proposed coding scheme in this dissertation results in a *design string* which is a set of numbers that refer to different codes classifying the data found in the design journals. The comparable codes from this dissertation with Jain and Sobek's are shown in Table 15 with the exception of the system and detail codes. These groups of cognitive codes are used to compare the results from this study with the study done by Jain and Sobek. The "other" category in Table 15 shows that this dissertation's proposed cognitive coding scheme has a level of detail that is beyond what the Jain and Sobek coding scheme captured.

Table 16 presents the proposed cognitive coding scheme results that are similar to the concept level coding scheme results from the Jain and Sobek paper [29]. These show that the proposed cognitive coding scheme can collect similar information to the previously published one.

The results shown in the table for Student Design Study 3 are only from the conceptual design phase of the project. The results shown in the table from the Jain and Sobek paper are only from the concept part of the coding matrix shown in Table 14.

Table 15: Comparing Coding Schemes: Jain and Sobek [29] and this Dissertation

Cognitive Codes used for Validation with Jain and Sobek Design Study	
Jain and Sobek Design Related Activity Coding Scheme	***Cognitive Coding Scheme***
Concept (C) – *addresses a problem or sub-problem with preliminary ideas, strategies, and/or approaches* [29] (p.62)	
Problem Definition (C/PD) – *gathering and synthesizing information to better understand a problem or design idea through activities such as: stating a problem, identifying deliverables and researching technologies*[29] (p.62)	Customer Requirements (2) Problem Statement Clarification (3) Criteria Lists (17) Search (1) Questioning (11) Assumptions (9) Definitions (36)
Idea Generation (C/IG) – *those in which teams explore qualitatively difference approaches to recognized problems, such as brainstorming activities, listing of alternatives, and recording "break- through" ideas*[29] (p.62)	Project Ideas (4) Analogical Reasoning (8)
Engineering Analysis (C/EA) – *formal and informal evaluation of existing design/ideas(s), e.g. mathematical modeling and decision matrices*[29] (p.62)	Engineering Characteristics (37) Testing Procedure (12) Material Options (6) Explanations (16)
Design Refinement (C/DR) – *modifying or adding detail to existing designs or ideas, deciding parameter values, drawing completed sketches of a design, and creating engineering drawings using CAD software*[29] (p.62)	Estimates (7) Calculations (10) Variables (13) Recommendations (14) Conclusions/Results (15) Design Changes (18) Mistakes (30)
Other (these codes don't apply in any of the Jain and Sobek categories)	Codes that don't apply: Revelations (22) Illegible Entry (33) Designer Signature (34) Other/No Evidence of Cognitive Activity (35) Meeting Notes (23) Price Quotes (26) Task Completion (27) Field Trip Notes (29)References (5) Personal Notes (19) Design Process Notes (20) Acquired Items (25) Project Milestones (28) Cross References (31) Task Assignment (24) To Do Lists (21)

The Jain and Sobek study's methodology is more similar to the studies presented in this work than the Atman study, but the types of design projects and the study administration was still different. The studies time periods are the same.

Table 16: Comparison with Jain and Sobek [29] Paper

Findings from the Jain and Sobek Design Study Compared to Proposed Cognitive Coding Scheme Findings	
Jain and Sobek Result *From design journals in a senior capstone design course*	*Student Design Study 3 (SDS3) Comparable Results from conceptual design phase only*
1. "Teams in the sample spent an average of 13.14% of their total design effort on concept level PD activity" [29] (p.65)	1. The students recorded an average of 18% of their journal entries on concept level PD activity
2. "Teams in the sample spent an average of 4.41% of their total design effort on concept level IG activity" [29] (p.65)	2. The students recorded an average of 46% of their journal entries on concept level IG activity
3. "Teams in the sample spent an average of 2.94% of their total design effort on concept level EA activity" [29] (p.65)	3. The students recorded an average of 5% of their journal entries on concept level EA activity
4. "Teams in the sample spent an average of 1.39% of their total design effort on concept level DR activity" [29] (p.65)	4. The students recorded an average of 6% of their journal entries on concept level DR activity

These comparisons show that the coding scheme in this dissertation is able to track the amount of dedicated time spent on different design activities and collect comparable information to that found by Jain and Sobek [29]. The results shown in Table 16 do not match exactly and this can be explained by noting course's differences.

3.5.3 Suwa and Gero (1998)

Suwa et al. (1998) presented a cognitive coding scheme to track a designer's cognitive actions using verbal protocol analysis data [11]. The study used a protocol analysis approach on a practicing architect designing an art museum while talking aloud and also making sketches on tracing paper for the museum. The specific time of the design task was 45 minutes.

Four levels of codes were chosen to describe cognitive actions: physical, perceptual, functional, and conceptual.

- *"Physical refers to actions that have direct relevance to physical depictions seen on paper"* [11] (p. 460)
- *"Perceptual refers to actions of attending to visuo-spatial*[1] *features of depicted elements on sketches"*[11] (p. 460)
- *"Functional refers to actions of conceiving on non-visual information which depicted elements and their visuo-spatial features are able to carry"* [11] (p. 461)
- *"Conceptual refers to cognitive actions that are not directly suggested by physical depictions or visuo-spatial features of elements"* [11] (p. 462)

These four cognitive actions include a finite set of design actions that belong in each level. The order of these actions support what cognitive scientists propose about the way information is processed in humans. The first level of processing is sensory which corresponds to the physical actions. The second level is perceptually and semantically which corresponds to the perceptual, functional and conceptual actions. Examples of physical actions are those relating to depictions made on the paper. Examples of perceptual actions are attending to shapes, making a grouping, and finding similarities. Examples of functional actions are exploring the drawn figure's interactions with people and considering the motivations of people. Examples of conceptual actions are making preferences for items and memory retrieval. The frequency of the three levels of functional, perceptual, and physical design actions

[1] The author of this dissertation interprets visuo-spatial as relating to the visual perception of spatial relationships among objects.

were coded from the design pages produced by the architect. The study researchers concluded that the design process used by the architect contained three phases: problem analysis, spatial arrangement, and functional exploration.

The studies done for this dissertation did not video or audio record any designer's actions so the *physical* action category will not have any meaning for this dissertation. The Suwa and Gero [11] study shows a side of design research from the architectural or industrial design perspective, which is different than the engineering designer's. Although the methods are different there are connections between the cognitive activities needed to create something new from nothing. The conceptual actions of Suwa and Gero's [11] study are important for comparisons with this dissertation's cognitive coding scheme because they are exclusively related to cognitive actions.

Suwa and Gero [11] propose three types of conceptual actions: designer's preferential evaluation treatment, setting up goals, and retrieval of knowledge from memory. One of their findings from reviewing the architects 7 pages of sketches is that he used *"three distinct design phases: problem analysis, spatial arrangement, and functional exploration"* [11] (p. 476). The other finding is that the cognitive actions found in the data are characteristic of specific design phases. In the words of Suwa and Gero:

- *"Functional actions occur more frequently in the phase of functional exploration than in other phases"* [11] (p. 476)
- *"Physical actions dominate in the phase of problem analysis"* [11] (p. 476)

- *"The phase of spatial arrangement is intermediate between the two"*[11] (p. 476)

The cognitive coding scheme presented in this dissertation does not have the context needed to make comparisons with the Suwa and Gero study like the ones previously shown for Atman and Jain and Sobek. The physical and verbal responses used in the Suwa and Gero study comprised a larger part of their coding scheme results and analysis.

3.6 Conclusions

In conclusion, coding schemes are useful in quantifying cognitive cues in design journal documentation. Applying any proposed coding scheme to a particular data set will reveal information needed and present a more robust coding scheme for application to future data sets. The verification process helped answer the question: Are we creating the coding scheme correctly? Planning for collecting the data may involve a short pilot study period to survey the level of participation that could be expected for future studies. A pilot study will also help the researchers understand the motivation of students to record design journals. Using current published research to validate the coding scheme provided proof that similar information can be collected.

Chapter 4: Journal Coding Process

The journal coding process describes the steps taken to categorize the design journal data into a format that can be analyzed. This chapter details how the journal coding process was done. The journal coding process developed a *design string,* which includes design sessions, design segments, design phase, concept codes, cognitive codes, and visual codes. First (Section 4.1), the details and components of the design string are given. Next (Section 4.2), the segmentation process is explained and a step-by-step journal coding example is presented. Section 4.3 presents the coding process for the professional's design journal, which is slightly different from the student design journals. Finally, in Section 4.4, inter coder reliability analysis is presented for the cognitive coding scheme.

4.1 The Design String Elements

The journal coding process produces a *design string* for each journal entry of interest. A design string is defined as the set of 6 numbers assigned to a coded journal segment. The design string is made of numbers representing each component shown in Figure 9. The coding process starts with segmenting the design journal into design sessions and ends with coding for the visual type. The components of the design string are:

- **Design session** is a combination of written records found in the design journal that have occurred on a single date or during a single period of concentrated time that was given to the design task.

- **Design segment** is section of work within each session in the journal on the same design thought which can be described by a single cognitive code.
- **Design phase** code assigns one of the 4 phases of the design process to the segment: 1- conceptual design, 2-embodiment design, 3-detailed design, and 4-re-design.
- **Cognitive code** is one of a set of terms used to identify actions and thinking processes that are inferred by the documented records (Detailed in Chapter 3 in Table 11 Page 56).
- **Concept** is the code in the design string that indicates the concept (if any) to which the segment is referring.
- **Visual type** is the code that classifies a visual representations found in the design segment: 1- sketch, 2- CAD, 3- photo, 4- simulation, 5- line drawing, 6- electrical drawing, 7- chart/table, 8- free body diagram, and 9 – none.

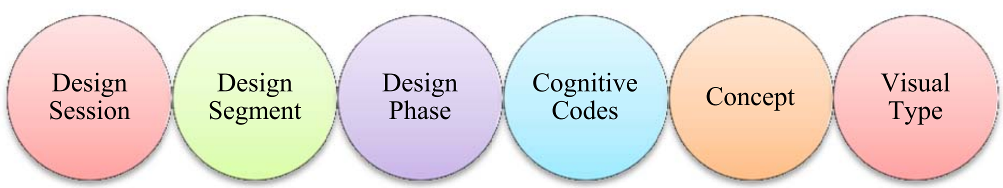


Figure 9: Elements of the design string assigned to each journal segment

For example a design string may be "1.3.2.4.1.1." (See Figure 10), in which each of the six elements correspond to an element describing information in the coded segment and the design session in which it is found. It organizes the coding process for the design records. The period between the numbers is used for space purposes only. This system also allows easy retrieval for revisiting the data when looking for specific information.

The number in the design string in Figure 10 is interpreted as follows:

1. First design session
3. Third design segment within the design session
2. Embodiment part of the design phase
4. Cognitive activity is project ideas
1. Relating to concept #1 found in this design journal
1. Visual representations type is a sketch

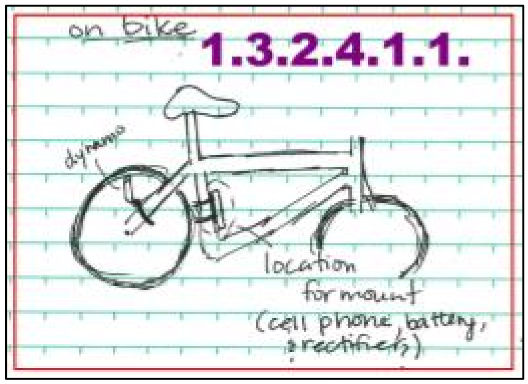


Figure 10: Design String Example from Student Design Study 2

Terms that are relevant to the proposed cognitive coding scheme and used throughout this document are journal, entry, and journal writer. A journal is a bound notebook with lined pages used as a permanent record of what happened during the design process, i.e. the development of the design. An entry is any record found in the design journal including (but not limited to) written text, sketches, and inserted design documents. The journal writer is the author of the design journal records.

4.2 Journal Coding Process for Students Journals

Researchers have proposed various types of journal coding processes [11, 29, 34, 36, 44, 71]. In order to extract quantitative data from the design journals a systematized plan had to be created to classify and evaluate the data. The design journals from Student Design Study 1-3 were collected and scanned for analysis. The steps A, B, C, D, E, and F in the journal coding process shown in the example in Figure 11 are presented in the following sub-sections 1 through 6 in that order.

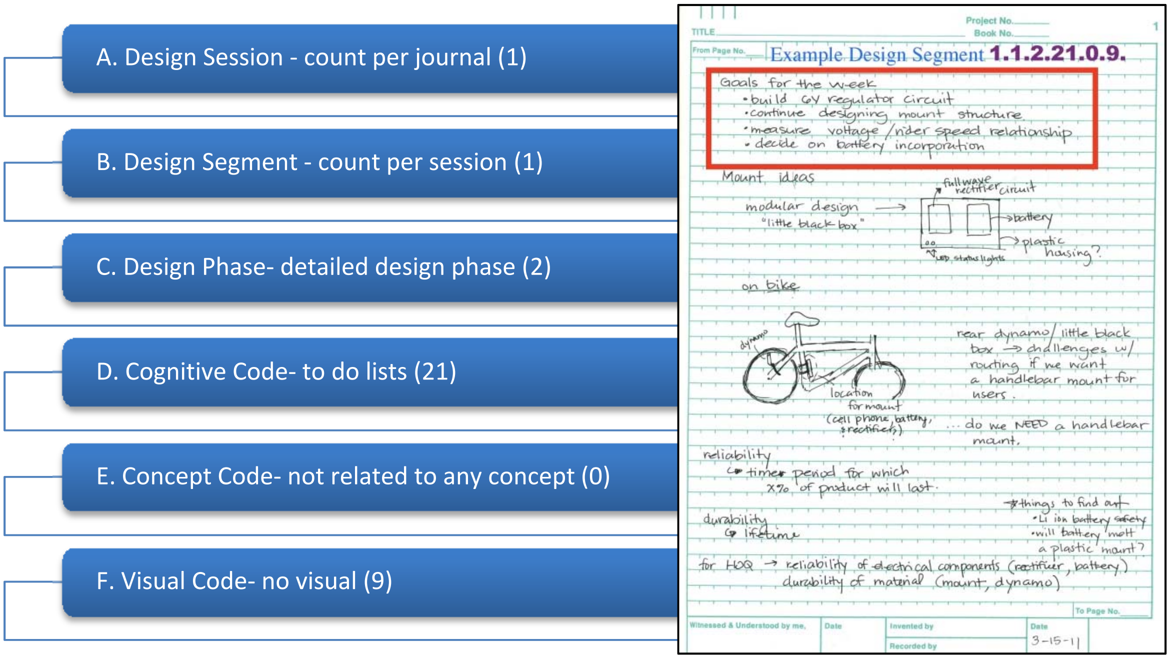


Figure 11: Design Process Coding Example

4.2.1 Step A: Journal Design Sessions

Meaningful segmentation of the design journal entries must be done in order to section them off to facilitate future analysis. Researchers have used a variety of methods for segmenting design data collected during design protocols. Atman et al. define segmenting as "*the process of breaking the verbal text into units (or segments) that can be coded with a pre-defined coding scheme*" [5]. Atman used sentences as a basic segment unit and further segmentation was done per sentence if it contained more than one idea. Grenier et al., investigating students' cognitive processes in design journals, segmented and coded every sentence or phrase in the each student's journal [78]. In Sobek's study of student design journals his research assistants coded each journal entry segment by date across the team. For example if a team had 5 members who each made an entry on May 1, all 5 of the May 1 entries were coded before the next dates in the set in order to view the design process from the point of view of each team member [32]. Ekwaro-Osire's research looked at the individual design process in sequential order and segmented first by date entry and then sub-coded by a tri-level rubric based on design level, creativity level, and context level [67]. Previous research methods of segmentation were based on the goals of the research and used to create coding protocols for extracting desired data.

The way in which the students' journal entries were segmented depended on several factors. One factor is how the students were instructed to make entries such as including a date and/or time whenever they made entries into their journals. Dated and timed entries make the segmentation process simpler by setting some boundaries. It can be difficult when entries are not dated because the coder is left to decide where the designer's recorded ideas and thoughts begin and end. The assumption was made that a cohesive design session will only occur in one day and hence is one design session. In rare cases that the student or professional designs through the night and intentionally changes the date at midnight, this is an unlikely occurrence.

The design session number is the first number in the *design string*. The students design journals were first segmented according to design session. This will separate the sequence of events into parts in order to help identify patterns. The dates delineated the *design sessions.* An example of a design journal session from Student Design Study 2 is shown in Figure 12. The date for this page is shown at the bottom to be April 3, 2011. The page is the beginning of "*design session 4*". In this example the student's insertion of a new date for this particular entry easily identifies the design session.

4.2.2 Step B: Journal Design Segments

The design segment number makes up the second number in the *design string*. The larger design sessions are divided into smaller design segments. The design thoughts create the smaller *design* segments. Separating sessions into segments is the most difficult task of the coding process.

The initial division of the sessions is often done by the journal writer themselves. There are various ways the beginning and end of a design segment can be recorded by the student. Ways the student can do this are by drawing straight lines between design activities, changing the time within the same date, and changing the color ink/lead used in the pen/pencil. Cohesion is indicated as "*continued*" or "*next page*" statements, arrows indicating a sequence or flow or representations (this means no segmentation may needed), and listing a topic for the design segment. Written text entries in paragraph form are sometimes segmented by blank lines, indented leading sentences, and numbered sentences (not lists). A design segment may be left undefined by the journal writer. If its focus is on the same design thought then it will be interpreted as one design segment.

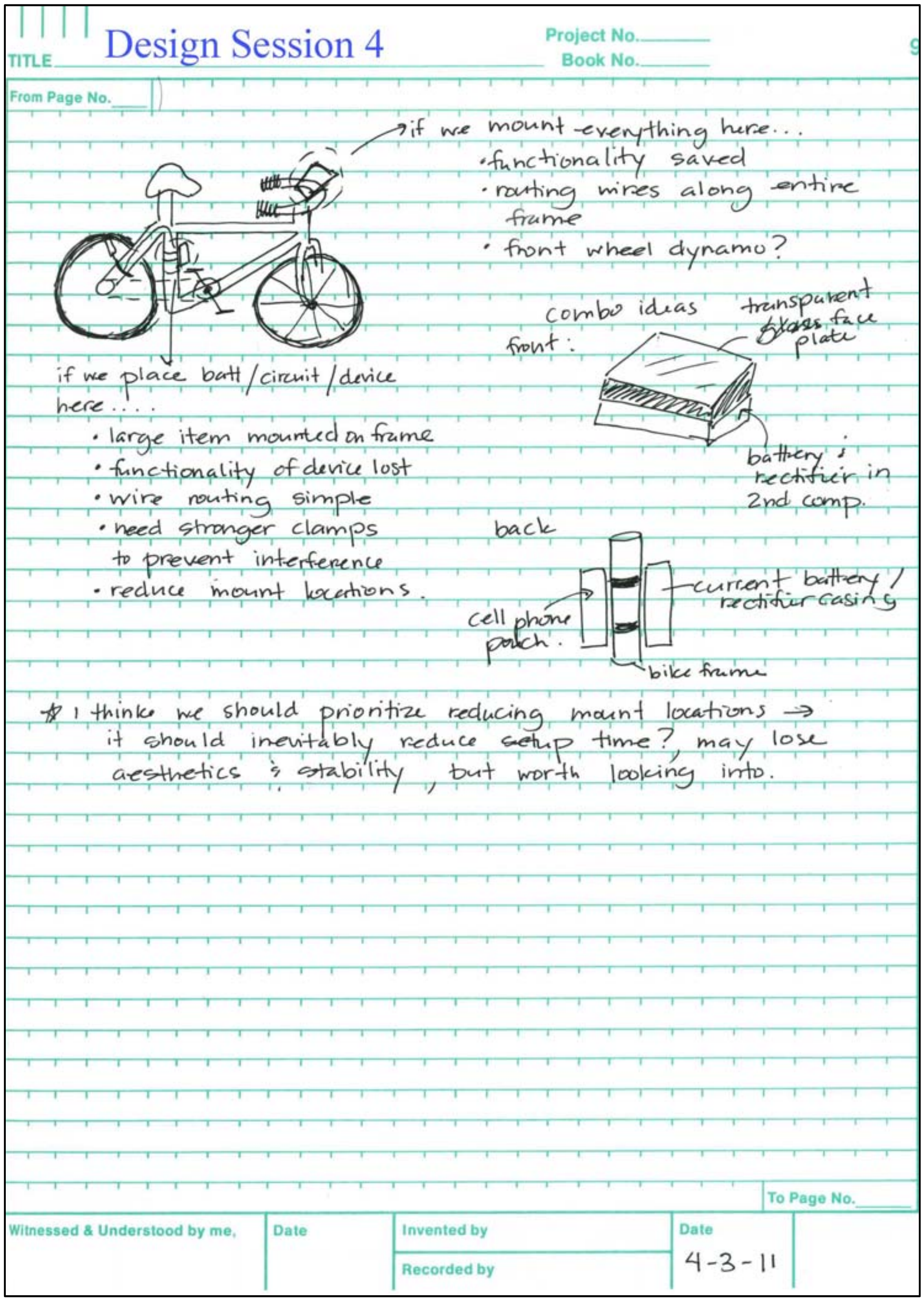


Figure 12: Design Session Example from Student Design Study 2

When a design segment is not defined by the journal writer the interpretation is left to the coder. Representations such as written text, equations, sketches, flow charts, etc. are considered a single design segment if the design thought is the same.

There may be multiple design thoughts included per paragraph requiring the coder to separate them out with different cognitive codes assigned to each one. The number of design segments in some design sessions is relatively high.

Not all journal writers are the same and, therefore, will not always provide these design segment division indicators. In this case the coder will interpret and manually section-off or divide the entries into design segments. Manual segmentation can be done by looking for spaces between entries, starting a new page when not necessary, labels for representations, and a change in the subject. An example of 7 design journal segments from Student Design Study 2 is shown in Figure 13. That session is divided as indicated by the large boxes. Each design segment is interpreted by the coder as unique design thoughts of the journal writer. The segments are then numbered starting with “1” in the design session they belong to and then in numerical order as they appear on the page.

Identifying design segments within sessions allows for comparisons between journal writers. These differences underscore the need to have a journal coding scheme that is specific. Additionally, the journal coding process must allow the researcher to label segments with enough detail that observations can be made about the cognitive activities of the students during the design process.

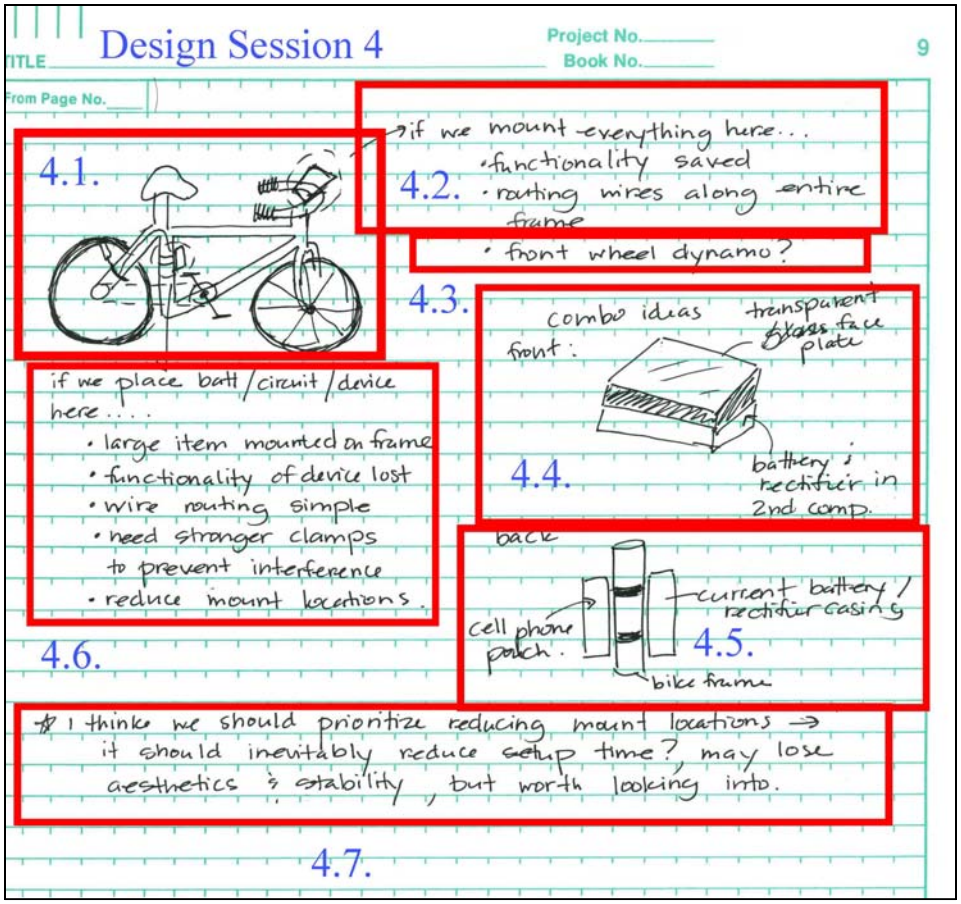


Figure 13: Design Segment Example from Student Design Study 2

4.2.3 Step C: Journal Design Phase Coding

The design phase code makes up the third number in the *design string* for each segment. Design phases are defined as stages in the engineering design process being used in the class. The design phase coding was done by design segments meaning that one segment can show evidence of only one design phase. The design phases used are as defined in *Engineering Design: 4th Ed.* as conceptual design (1), embodiment (2), detail design (3), and redesign (4) and can be seen with a more thorough explanation in Table 17 [8]. The design phases were coded by assigning the numbers 1 – 4 correlating to each of the 4 design phases.

Table 17: Design Phase Categories

Design Phase Categories for the Engineering Design Process	
Design phase	***Description***
Conceptual design (1)	The process by which the design is initiated, carried to the point of creating a number of possible solutions, and narrowed down to a single best concept. *This Includes*: Benchmarking, House of Quality, Patent Search, Functional Decomposition, AHP
Embodiment design (2)	Structured development of the design concept including the main functions to be performed by the product. *This Includes*: Product Architecture, Materials Selection, Manufacturing, Robust Design, DFM, DFA
Detail design (3)	The point when the design is brought to the stage of a complete engineering description of a tested and producible product. *This Includes*: Finalize PDS, set the dimensions for key parts, create engineering drawings
Redesign (4)	Stage done after testing to refine or change the design concept.
Other (5)	Does not clearly fall into one of the design phases

All students who participated in this study were in the Mechanical Engineering Capstone Design Course (ENME 472) which requires the text '*Engineering Design: Fourth Edition'* and therefore the definitions are directly applicable to this study [8]. The students in the course are required to follow the Product Development Process detailed in Chapter 2 (p.39) of the course textbook [8].

Segments that did not easily fall into one of the defined design phases were coded as other. The segments in the example continued from Figure 13 all belong to the embodiment design phase and therefore are coded as "2".

4.2.4 Step D: Journal Cognitive Coding

The cognitive code is the fourth number in the *design string.* The design journal segments were coded using the cognitive coding scheme detailed in Chapter 3. Figure 14 is an example of the cognitive code to-do lists from Student Design Study 3. The design phase for this example was conceptual design. The students have time, money, and resource limitations for their design project, which requires them to utilize project management skills. One such skill is making to-do lists, which are items that need to be completed for the project by the journal writer and also by other team members. This list includes three items that need to be done but does not specifically state who is going to complete them, whether the journal writer or another team member. The student including the title "To-Do in Class" makes it straightforward for the journal coder to identify this segment as a to-do list.

The author of this dissertation who has significant experience in design and a thorough understanding of the design process identified the cognitive codes in the design journals. The author also has experience reviewing design journal content and understanding the different stages of the design process. The cognitive class was first identified for each design segment and then the applicable cognitive code selected based on the definitions given in Table 11.

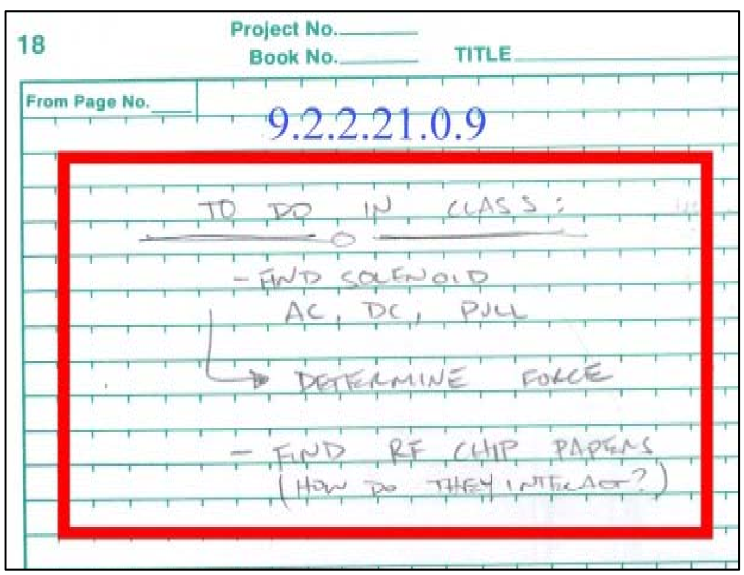


Figure 14: Cognitive Code Example of To Do Lists (21)

Two examples of the cognitive code project ideas are shown in Figure 15 that come from Student Design Study 2. The examples are outlined with the boxes. The design phase for this example was conceptual design. The student on this team in Student Design Study 2 was creating a device to power a cell phone or other small electronic device through USB on a bicycle. The two boxes show that the student was considering different options for setting up the parameters. The fact that this type of set-up appears twice on the page and the student numbered the different ideas leads the coder to the conclusion that these would be coded as project ideas.

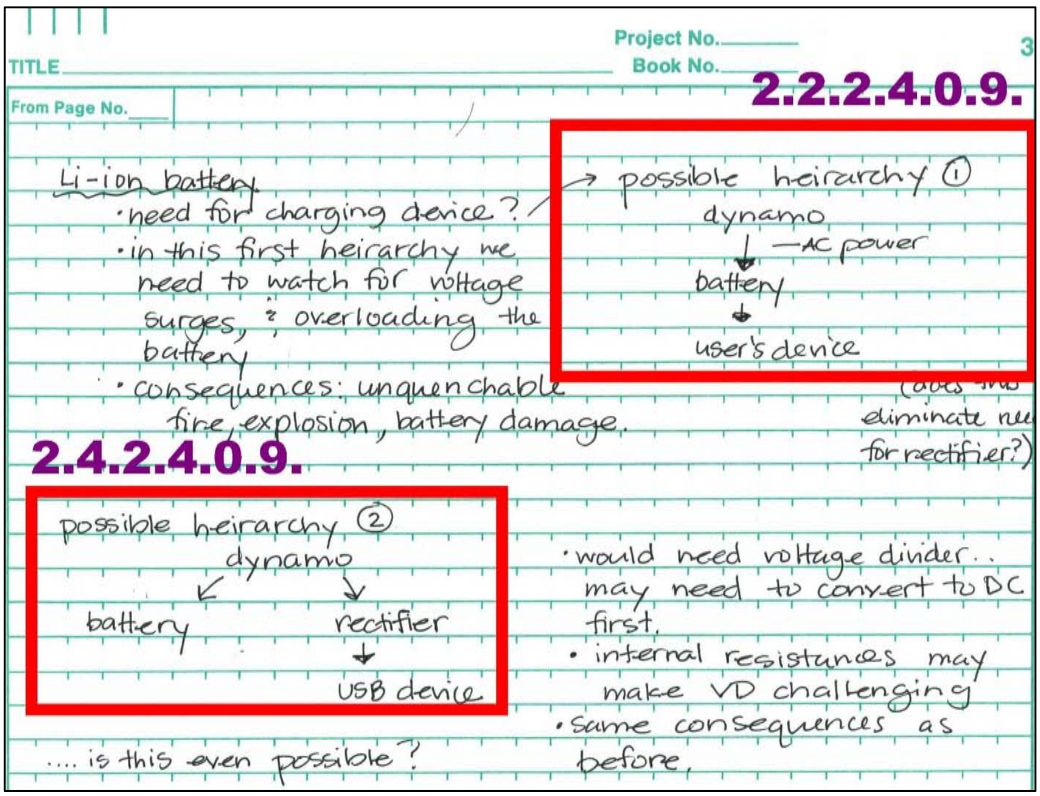


Figure 15: Cognitive Code Example of Project Ideas (4)

The example in Figure 16 shows the cognitive code for design changes from Student Design Study 2. A design change is a type of decision made a team to alter existing or previously chosen design requirements. The design phase for this example was re-design, which is unexpected for design project with such a short time period. This student actually labeled this section “Redesign Sketches” which made it clearer during the coding process to identify these sketches as design changes. The nature of design is that sometimes ideas and analysis don’t always produce the desired results and at times call for the re-design step in the design process. Each of the sketches shown in the figure below would have been coded a separate design segments.

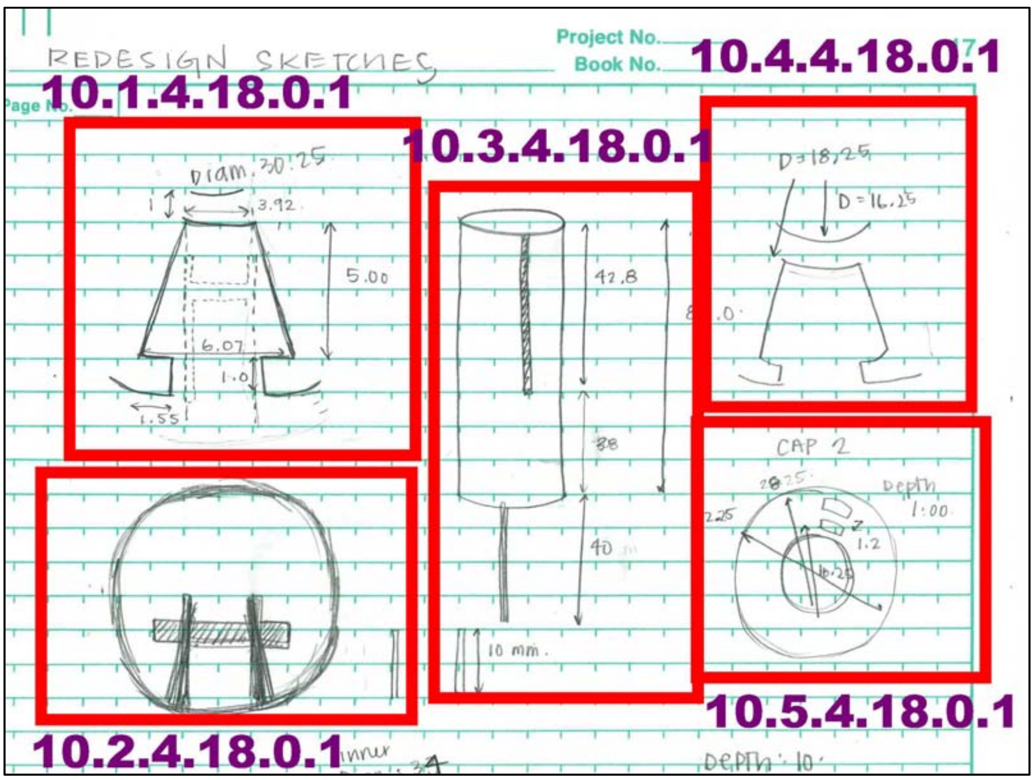


Figure 16: Cognitive Code Example of Design Changes (18)

The example shown in Figure 17 is of the cognitive code for customer requirements from Student Design Study 3. This project was to design a device that can harvest energy from human footsteps in busy metropolitan areas such as subways and high traffic sidewalks. The design phase for this example was conceptual design.

In this design segment the student was noting the differences in the speed of walkers that might utilize their device. The speed of the user is important for the amount of energy that can be captured by the device and re-used for another purpose. The effectiveness of this type of device depends on the amount of foot traffic, which is relative to the speed of the walkers. This type of statement can be used to describe the product requirements from the perspective of the customer. The example shown in Figure 18 is also of the cognitive code for customer requirements from a different student in Student Design Study 3.

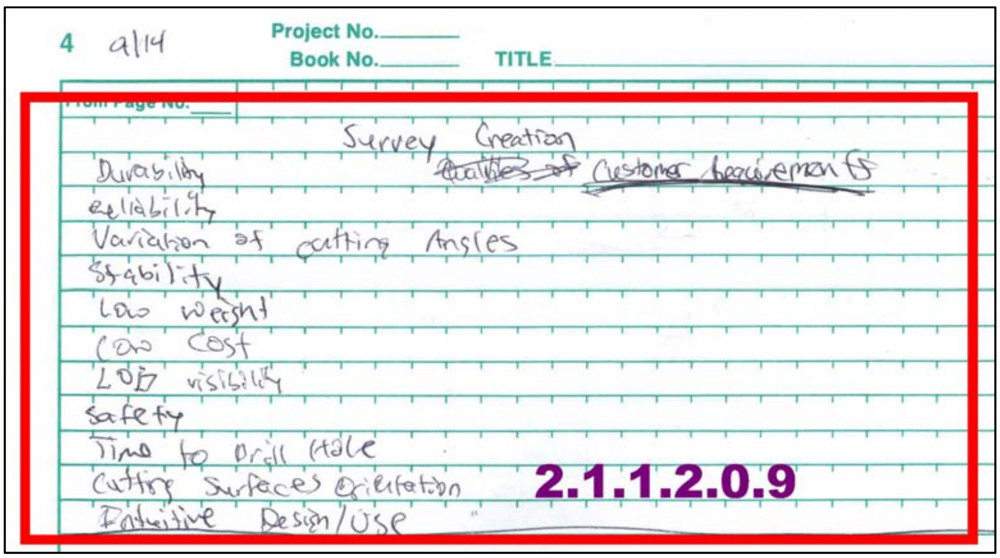


Figure 17: Cognitive Code Example of Customer Requirements (2)

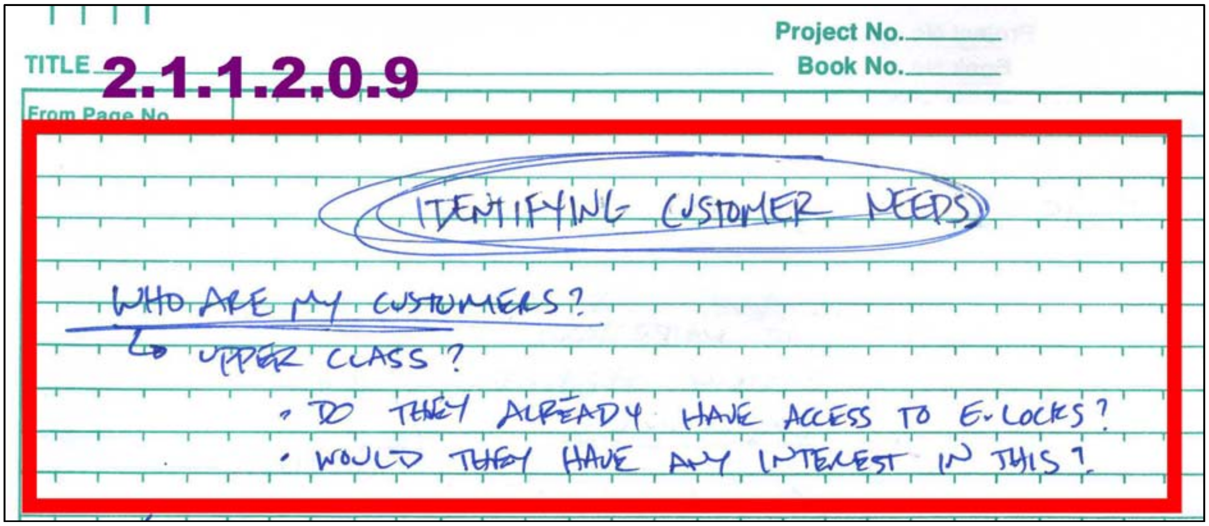


Figure 18: Cognitive Code Example of Customer Requirements (2)

Figure 19 is an example of the cognitive code for referencing from Student Design Study 3. References are found in the design journal as sources of information such as books, blogs, webpage's, persons, tables, and charts that include information that will be needed in the future. This example is unique because it shows a non-written design journal entry that is relevant to the design process and that can be included in the design journal coding process. The design phase for this example was embodiment. This project was to create an eco-powered camping tent and this reference information was most likely used to select a tent to use with the prototype. The team was not trying to build a tent so selecting and purchasing a standard camping tent was important for the project. This example shows ways in which students documented information that they were collecting for the design project. Searching for information to frame the design problem or solution is an important part of the design process.

Figure 19: Cognitive Code Example of References (5)

It is expected that there will be higher occurrences of certain cognitive activities during certain parts of the design process. Certain hypotheses that are shown in Table 18 are expected outcomes from the cognitive coding scheme. The class project management is not shown in this table because it is expected that there will not be significant differences across the different design phases for this class. The four hypotheses shown in the table are based upon where these classes traditionally show in higher numbers. The results will be shown in the next chapter (5).

Table 18: Hypothesis for Cognitive Activities in Different Design Phases

Design Phase Hypothesis for Conceptual Design		
H1: Information Seeking and Noting (1), Problem Understanding (2), and Idea Generation (3)	Greater than	All other Classes
Design Phase Hypothesis for Embodiment Design		
H2: Analysis (4)	Greater than	All other Classes
Design Phase Hypothesis for Detailed Design		
H3: Decisions (5)	Greater than	All other Classes
Design Phase Hypothesis for Re-Design		
H4: Reflection (7)	Greater than	All other Classes

A table with more examples of each of the cognitive codes can be found in the Appendix.

4.2.5 Step E: Journal Concept Coding

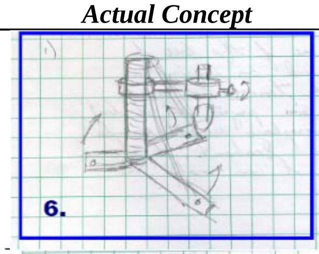
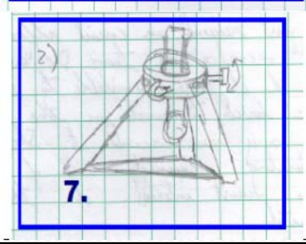
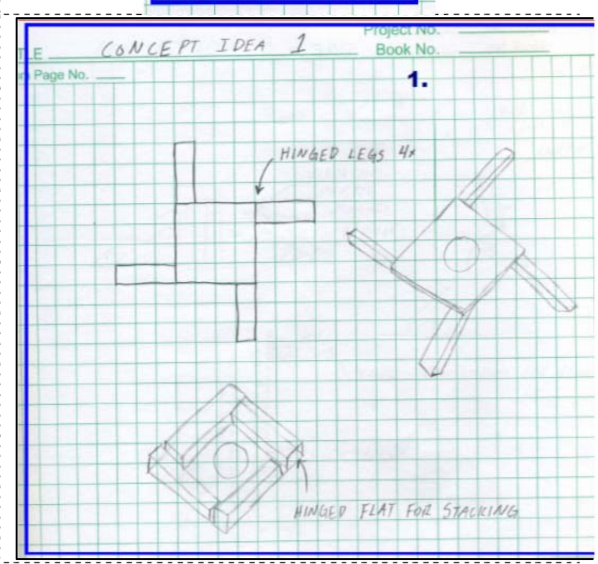
A code indicating the concept to which the action of the segment is related is the fifth number in the *design string*. This includes the initial ideas, embodiment ideas, detailed design ideas, final design, and components of the final design product. Developing the design of a new or improved artifact is the whole reason to participate in the design process. Students in the course were tasked with developing the design of a new or improved artifact.

The process first requires the generation of a number of alternatives for the artifact design. During design concepts are generated and recorded with the expectation that they may solve the design problem. Each alternative design is called a concept. The purpose of this coding for artifacts was to track concepts as multiple members of the same team adopted them. A concept or one of its modifications will ultimately develop into the final design.

Each concept appearing in a journal is assigned a number and all segments about that concept are labeled with that number. Each journal has a separate list of concepts found within that journal. Table 19 shows an example of concept codes 1-4 from one of the teams in Student Design Study 1 which is just part of the listing of concepts found from that team. The concepts were numbered as a way to track them across design journals and label them accordingly; regardless of in which member's design journal they appeared. The concepts shown in Table 19 come from two different students, which is apparent by the differences in the handwriting. Concept 1 and 2 belong to the same student and concept 3 and 4 to a different student.

A list of concepts was created for the entire team and tracked between the different students design journals for the *Team Study* group in Student Design Study 1. The initial purpose of concept tracing was to track concepts as they were generated and considered by multiple members of the same team. Tracking concepts will give some insights into the journal writer's adaptation of concepts not their own and also team member participation among the students.

Table 19: Concept Code List Example from Student Design Study 1 (Team Study)

Concept Number	***Actual Concept***
1	
2	
3	

4

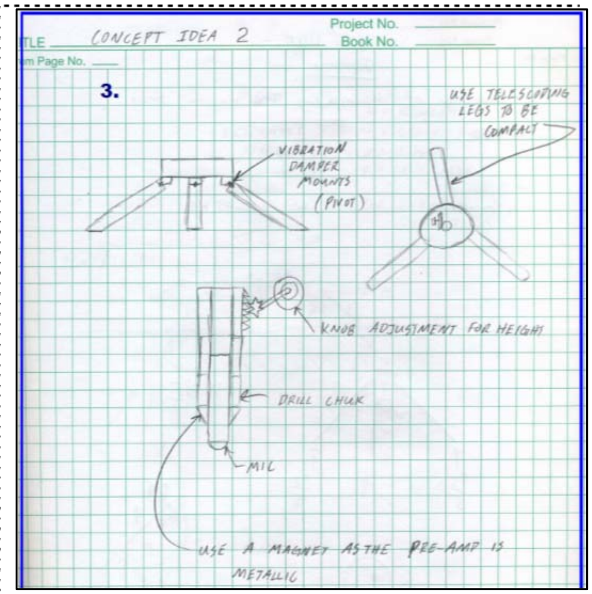


Figure 20 shows an example of how different concept references might occur in a student's journal regardless of the author. Here the student is listing advantages and disadvantages (using yellow sticky notes) of the different concepts created by the other team members.

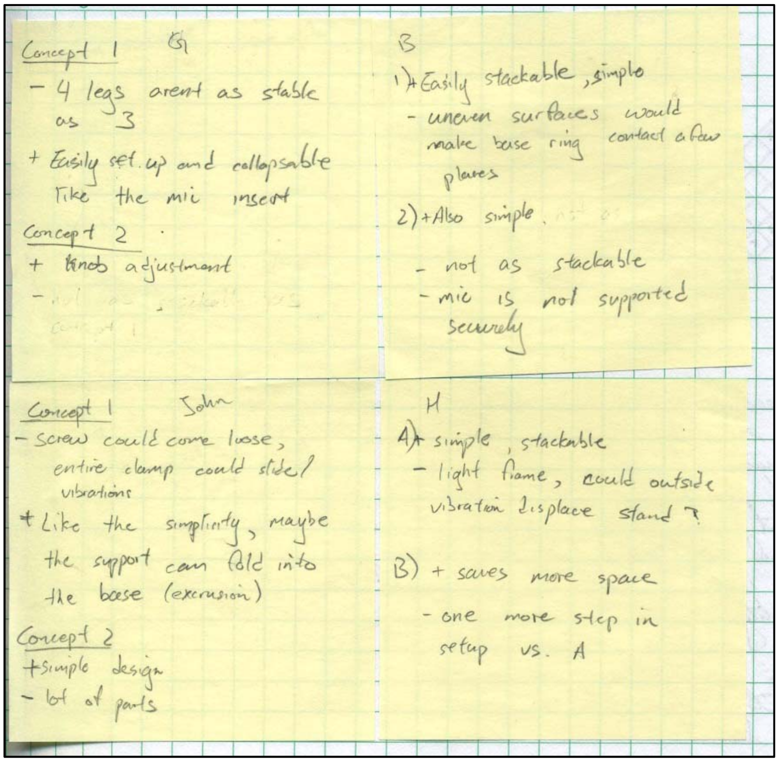


Figure 20: Concept Example from Student Design Study 1

Figure 21 shows an example of how the concept codes are coded in the design journal.

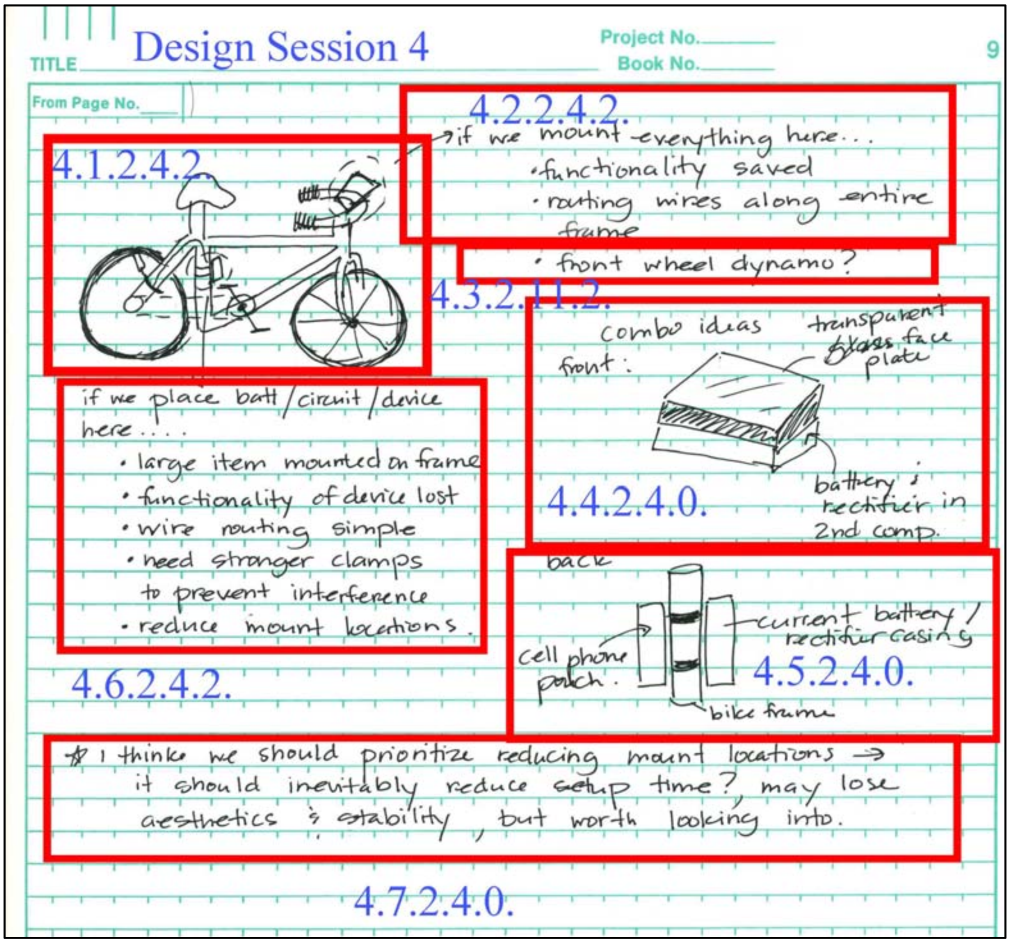


Figure 21: Concept Code Example from Student Design Study 2

The concept example shown in

Figure 22 is a reflection that the student was writing in the design journal that mentions which concept was chosen to move forward. This is a unique way in which a concept was mentioned that was not created by this particular journal writer. The students name is mentioned as the creator of the final concept. The concepts that originated in another students journal are then counted as being referenced here by this journal writer.

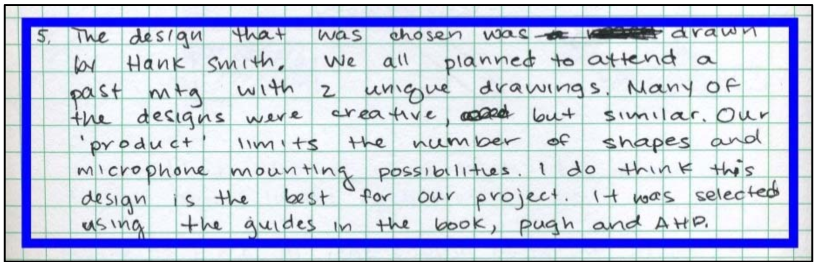

5. The design that was chosen was drawn by Hank Smith. We all planned to attend a past mtg with 2 unique drawings. Many of the designs were creative, but similar. Our 'product' limits the number of shapes and microphone mounting possibilities. I do think this design is the best for our project. It was selected using the guides in the book, pugh and AHP.

Figure 22: Concept Code Example from Student Design Study 1

Figure 23 is another example from the concept part of the coding process from Student Design Study 3. This student labeled each concept with a number, which made it clear that they were different. Also in this design journal the student's concepts were all found one page after another during the conceptual design part of the design process.

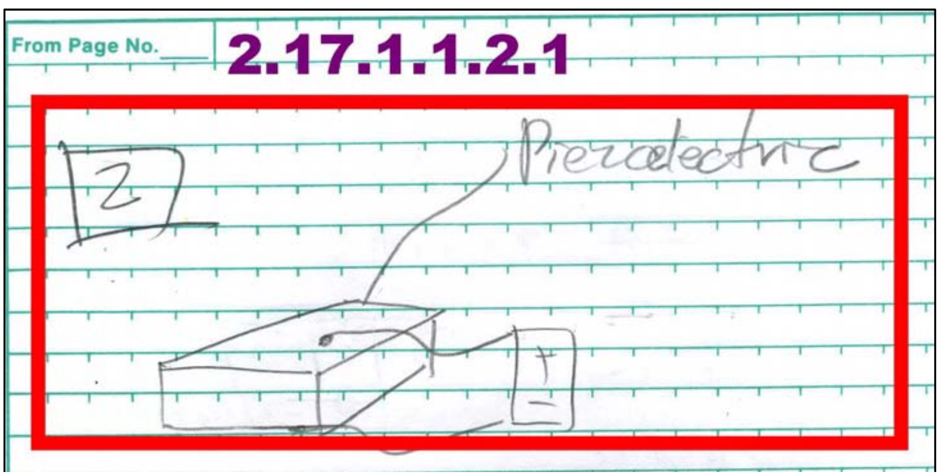


Figure 23: Concept Code Example from Student Design Study 3

4.2.6 Concept Referencing Ratios

Nomenclature

C_j^M = set of all concepts appearing in journal *j*

C_{jl}^M = set of all concepts appearing in journal *j* originated by member *l*

I^M = set of all concepts generated by members of team *M*

M = identification number for a design team from ($1, 2 \ldots T$), where T is the number of teams
N_j = number of concepts that appear in journal j
S_j = total number of referencing instances appearing in journal j
c_{jkl}^M = k^{th} concept appearing in journal j on team M; this concept is originated by member l; $j=1, 2 \ldots m^M$ and $l=1, 2 \ldots m^M$
j = identification number for each member of a design team M; j=1, 2…m^M
k_M^* = final design concept selected for team M
m^M = number of members on design team M
n_{jk} = number of times concept k appears as a referencing instance in journal j
r_j^s = self concept reference ratio
r_j^o = others concept reference ratio
r_j^t = team concept reference ratio
r_j^f = final concept reference frequency ratio

The coding scheme allows quantification of a subject's documentation of concepts generated by the team. It is expected that a student will use a design journal to document and develop their own concepts prior to a team's selection of a final design concept. A very thorough design journal will also include references to the concepts generated by other team members during the conceptual design phase. After conceptual design, thorough journals would reference only the final concept selected by team and any variations to it (embodiment, detail, and redesign phases).

Metrics based on the number of references in a journal to the journal-writer's concepts, team members' concepts and a team's final concept are instructive. These metrics can suggest the amount of participation outside of their individual concept generation process as a team member.

A *concept* is one that is clearly defined by the students with a label. A concept can also be final assembly of the product that was not previously seen in the journal. The concepts appearing in a student's (j) journal on team M make up a set as shown in Eq. (1). The size of the set will vary. Team concepts were coded, as they appeared in the journals, which were coded in random order, each concept appearing in a journal will have a numeric identifier (*k*).

$$\mathcal{C}_j^M = \{\, c_{jkl}^M | \forall j \in M; \forall\, k\, , and\ \forall l\,\} \tag{1}$$

where *j* is the member whose journal is being coded and *l* identifies the team member who originated the concept. Equation (2) defines the set of concepts appearing in the journal of member *j* but originated by team member *l*.

$$\mathcal{C}_{jl}^M = \{\, c_{jkl}^M \,| \forall j \in M; \forall\, k\,\} \tag{2}$$

Establishing authorship of concepts that appear within several team members' journals is difficult. Some team members gave attribution to the concept originators. (This should be the case in good journaling practice.) Otherwise the date is used to determine the concept originator.

In team design project courses members generate a set of several concepts from which to select an alternative to develop during embodiment design. Equation (3) defines the set of all concepts generated by team *M*.

$$I^M = \bigcup_{j=1}^{m^M} \mathcal{C}_j^M \tag{3}$$

In Eq. (3) a union (emphasizing the "and/or" declaration) constitutes the set of all distinct concepts appearing across the journals of team *M*. One of the concepts generated by the team will be selected as the final concept (k_M^*) emerging from the conceptual design process.

A *concept reference* is defined as a distinct journal entry (or segment) that is associated with a concept. Equation (4) defines the sum the frequency of concept references appearing in journal *j*.

$$\mathcal{S}_j = \sum_{k=1}^{N_j} n_{jk} \tag{4}$$

where n_{jk} is the number of times concept *k* appears as a referencing instance in journal *j*.

Several concept reference ratios were developed to quantify the students' referencing behavior. These ratios indicate the involvement of the journal writer with concepts developed and discussed by the team. The *Self Concept Referencing Ratio* (r_j^s), shown in Eq. (5), compares the set of concepts referenced in journal *j* created by member *j* with the set of all concepts referenced in journal *j*. In other words r_j^s is the percent of time the student referenced their own concepts.

$$r_j^s = \frac{|C_{jj}^M|}{|C_j^M|} \tag{5}$$

The *Others Concept Referencing Ratio* (r_j^o), shown in Eq. (6), compares the set of concepts referenced in journal *j* not created by member *j* with the set of all concepts referenced in journal *j*. In other words r_j^o is the percentage of time the student references other team member's concepts.

$$r_j^o = \frac{|C_j^M| - |C_{jj}^M|}{|C_j^M|} \tag{6}$$

The *Team Concept Referencing Ratio* (r_j^t), shown in Eq. (7) compares the set of all team *M* concepts that appear in journal *j* with the set of all team *M* concepts created.

$$r_j^t = \frac{|C_j^M|}{|I^M|} \tag{7}$$

The *Final Concept Referencing (Instance) Ratio* (r_j^f), shown in Eq. (8) compares the referencing instance of the final design concept of team *M* with the referencing instance of all team *M* concepts created. Referencing instance is defined as the frequency of entries appearing in the student's journal. r_j^f is different than the previous three because it counts referencing instances and not just one single reference. For example a team member may reference concept *k* up to *n* times and each of those are counted for in r_j^f.

$$r_j^f = \frac{n_{jk_M^*}}{s_j} \tag{8}$$

4.2.7 Step F: Journal Visual Coding

A code for the visual type in the segment (if one is included in the segment) is the sixth and final number in the *design string.* The visuals included in the design journal are a very important part of telling the design story. Westmoreland et al. provided the foundation for a visual component to this coding scheme by defining four categories of visual representations including: sketch, line drawing, CAD, and Photograph [75]. These codes were expanded during the research for this dissertation into the visual codes shown in Table 20. A visual representation part of the coding process was added after the professional's design journals were coded because similarities found with the students design journals.

Table 20: Visual Code Categories

Visual Code Categories and Descriptions	
Visual Code	***Description***
Sketch (1)	A sketch is a drawing that is done without concern for detail in order to capture a general idea. A sketch is made without the use of any instruments, such as a straight edge [75].
CAD (2)	A CAD is a visual image created with a formal computer aided drawing package (e.g., AutoCAD, Pro/ENGINEER, and Solid Works) [75].
Photo (3)	A photograph is an image that is produced with the use of a camera. The image is an exact replica of what the human eye would perceive at an instant in time [75].
Simulation (4)	A FEA (Finite Element Analysis) simulation visual is created with formal computer aided software such as Solid Works. It produced a model of a design or component with stresses and loads for analysis.
Line Drawing (5)	A line drawing is a picture made of lines created by hand or by computer; drawn with assistive instruments. A visual made with the drawing tools of a word processing software falls into this category [75].
Electrical Drawing (6)	An electrical drawing, also known as a flowchart, represents the electrical current in a system. The drawing is created with standard electrical symbols such as resistor, capacitor, power supply, lamp, and transistor.
Chart/Table (7)	A chart is a graph that presents a set of data usually representing the numbers as bars or dots. A table is an organized text box that also presents a set of data usually numbers.
Free Body Diagram (8)	A free body diagram is a drawing used to visualize the forces acting on an object and uses physics principles to depict the object in a given situation. This visual made by hand or with the computer usually contains a box, arrows, and force values.
None (9)	None of the other codes apply

Figure 24 shows an example of the visual codes in the design journal from Student Design Study 3. This example the student included a sketch (1) while generating different concepts for their design project.

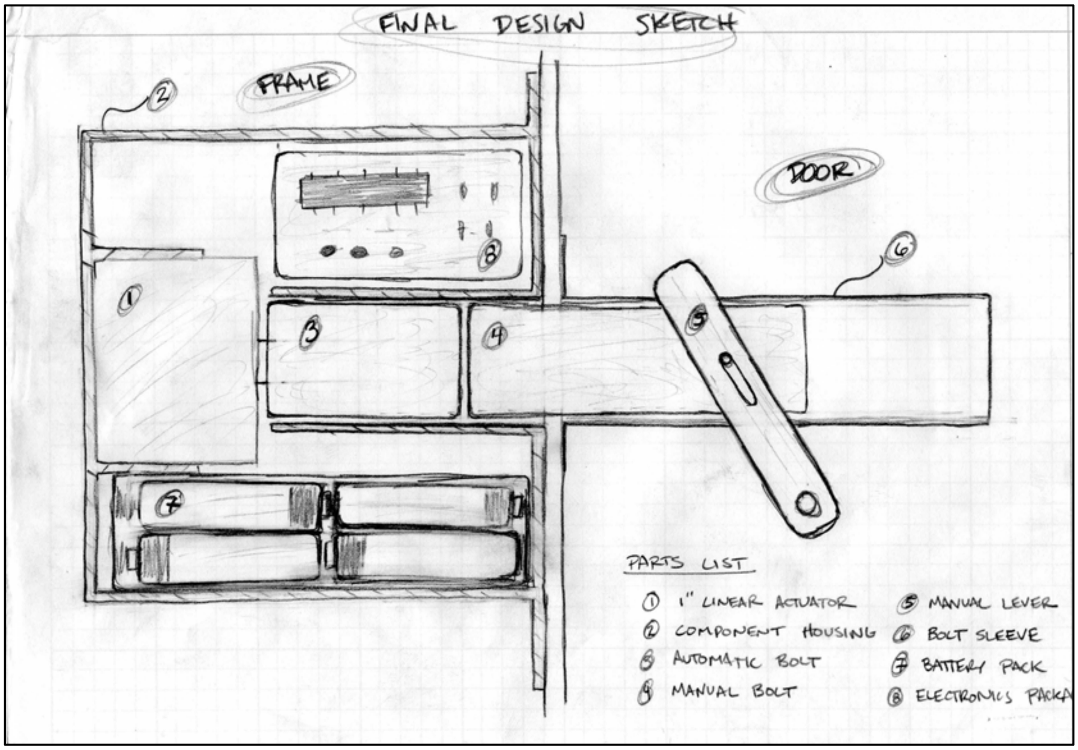


Figure 24: Visual Code Sketch Example

Figure 25 shows an example of the visual codes in the design journal from Student Design Study 3. This example is a photo (3), which was found in the design journals as a visual representation of project ideas.

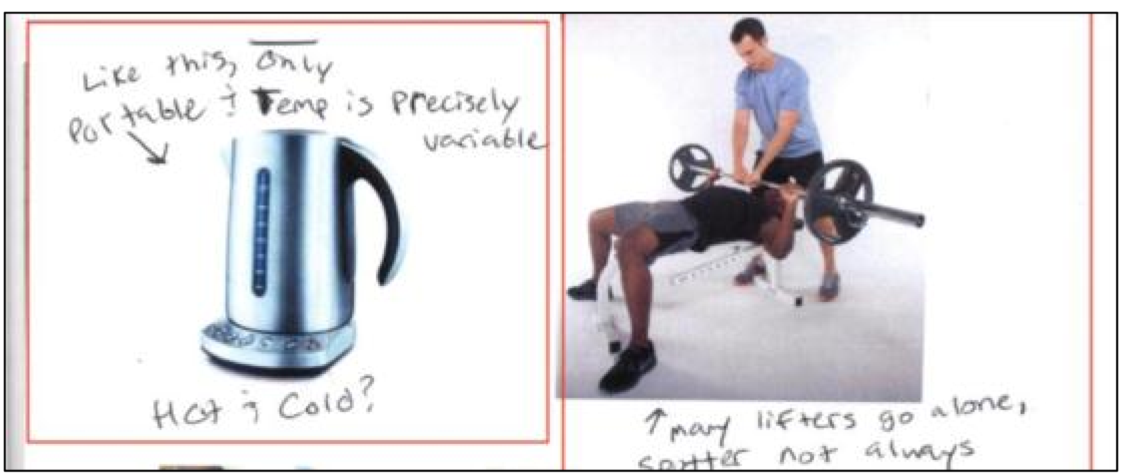


Figure 25: Visual Code Photo Example

Figure 26 shows an example of a visual in the design journal from Student Design Study 3. This example is a CAD drawing (2) of a component found in the students design journal as an inserted page. The CAD drawings (2) are important for students and required as a part of their final design reports for the capstone design course.

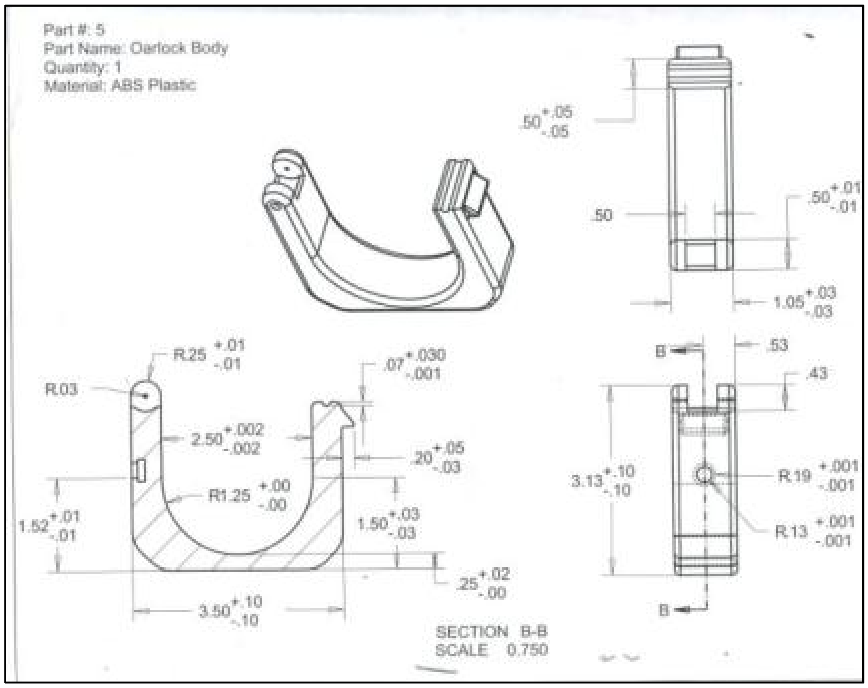


Figure 26: Visual Code CAD Example

Figure 27 shows an example of the visual codes in the design journal from Student Design Study 3. In this example an electrical diagram (6) is drawn by the student to show a possible electrical set up.

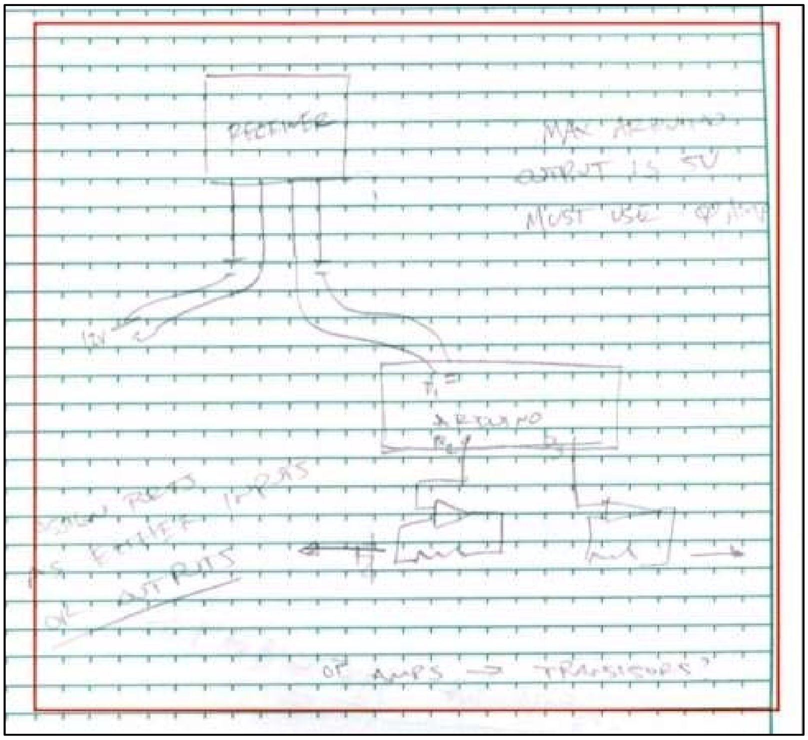


Figure 27: Visual Code Electrical Diagram Example

The six codes in the *design string* previously described were applied to the design journals and then the data was entered into a spreadsheet for analysis. The setting of this study is considered natural or *in situ*, which can account for some inconsistencies in the data collected.

4.3 Journal Coding Process for Professional Journal

The way in which the professional's design journal was segmented was the same as the students with one exception. The professional's design journals were not scanned but coded directly into Excel using the same journal coding process as the students. The design journals from the professional were coded by hand on location with the designer for confidentiality.

Although the professional engineer did not use the same course textbook and specific instructor guidelines he did use a similar process that he described in the exit interview. The professional designer's employer did not mandate a specific design process so he reverted to design experiences from previous design jobs he held and also remembered the design process he learned in college. Tracking concepts in the professional's journal was challenging due to the nature of the project he was working on. As the lead mechanical engineer on the project he was responsible for working on several components at one time. Different iterations of various components were found but hard to track in his journals. He wrote three design journals with many pages for this particular project. Tracking the conceptual development of all these components across many journal pages is what made the task challenging.

Figure 28 shows an example of the notations made by the author while coding the professional's first design journal. Initially the journals codes were written and then manually input into Excel spreadsheet for analysis. The lists shown were made during the coding of the professionals design journal 1. The purpose was to identify the concepts by a name or title that is found to be recurring in the professional's design journal. Even this was challenging because the professional did not always make a reference or call specific components by name. Since this was his project it is assumed that he probably didn't need to for every single reference to a components concept.

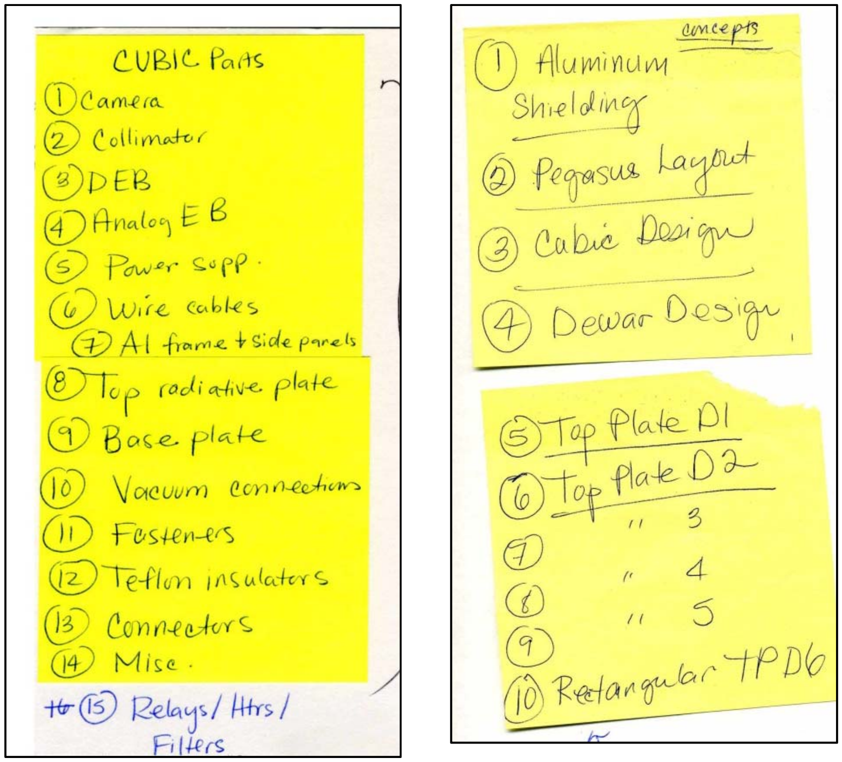


Figure 28: Concept Coding Lists Made for the Professionals Design Journal

Figure 29 shows a sample from the hand coding of design journal 1 in the set of professional’s design journals. Looking at the lettering going down the middle of the page “E” is the concept code. The three design segments shown here each refer in some way to the aluminum shielding which is “1” from the right list in Figure 28.

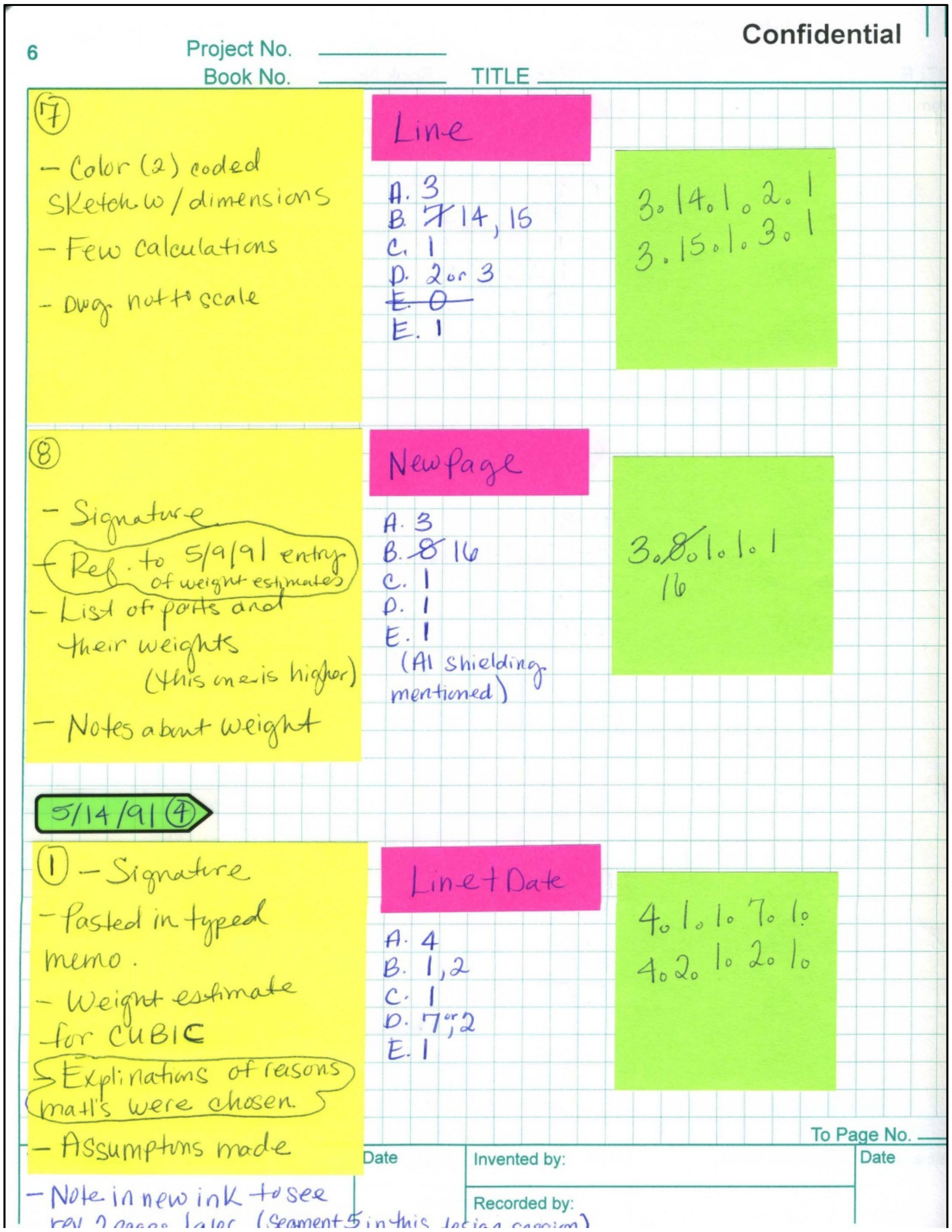


Figure 29: Sample Concept Coding Notes for the Professionals Design Journal

4.4 Inter Coder Reliability

The main coder for the Student and Professional design studies is the author of this dissertation who is an advanced graduate student with a background in design knowledge. For the reliability study, an undergraduate research assistant also coded 25% of the design journals from Student Design Study 2 and Student Design Study 3 using the cognitive code of the design string only. The design journals coded by the undergraduate research assistant were pre-segmented by the main coder. The undergraduate research assistant is a sophomore mechanical engineering major at the University of Maryland- College Park. The main coder trained the undergraduate research assistant by the following steps:

1. Review of relevant literature that included journal papers on the subject of segmentation, design journal studies, and design coding schemes. [4, 30, 32, 68, 75]
2. Review of the cognitive codes including definitions and examples. Also reviewed the proposal (unpublished) written for this dissertation by the main coder.
3. Independent coding of 5 previously coded sample pages by the research assistant and the main coder simultaneously followed by discussion about the differences. Out of 42 coded segments the agreement between the main coder and the research assistant was 30 or 71%. The codes with the highest percentages of differences were project ideas (41% out of the 12 non-agreed codes) and assumptions (25% out of the 12 non- agreed codes). The reason for the discrepancies with these two codes is because a project idea can be presented with underlying assumptions that are not explicitly stated by the journal writer. For example a student may suggest that the project be marketed

in the Baltimore-Washington region which could also be seen as an initial assumption for market share.

4. Repeat the independent coding of 5 previously coded sample pages (new set from #2) by the research assistant and the main coder simultaneously followed by discussion about the differences. Out of 32 coded segments the agreement between the main coder and the research assistant was 18 or 56%. The codes with the highest percentages of differences were personal notes (22% out of the 14 non-agreed codes) and recommendations (27% out of the 14 non-agreed codes). Each discrepancy was discussed and a resulting code was agreed upon.
5. Repeat the independent coding of 5 previously coded sample pages (new set from #2 and #3) by the research assistant and the main coder simultaneously followed by discussion about the differences. Out of 16 coded segments the agreement between the main coder and research assistant was 16 or 100%. This completes the undergraduate research assistant's training for the journal coding process.
6. The undergraduate assistant coded of 25% of the Student Design Study 2 journals which came out to one full design journal. Out of 66 coded segments the agreement between the main coder and the research assistant was 42 or 63%.
7. The undergraduate assistant coded 25% of the Student Design Study 3 journals which came out to two full design journals. For journal 1 out of 99 coded segments the agreement between the main coder and the research

assistant was 41 or 41%. For journal 2 out of 123 coded segments the agreement between the main coder and the research assistant was 31 or 25%.

Table 21 shows the raw agreements and Cohen's Kappa (-1 to +1) for the three samples done for inter coder reliability. The first two samples show good agreement according to Kappa scale interpretations. The third sample shows fair agreement according to the Kappa scale. The second coder will undergo additional training and code another journal sample from SDS3 to provide a third rating comparison.

Table 21: Inter Coder Reliability Results

Inter Coder Reliability Results				
Sample	***Study***	***Segments***	***Raw Agreement***	***Cohen's Kappa (-1 to +1)***
A	1 journal from SDS2	66	0.64	0.6207
B	1 journal from SDS3	99	0.41	0.6471
C	1 journal from SDS3	123	0.25	0.2198

4.5 Conclusions

The journal coding process starting with segmentation of the design journals is time consuming yet provides the rich data set found in this dissertation. The concept referencing ratios can be applied to other types of design documentation such as verbal protocol analysis studies data. Including the professionals design journal in this study helped to expand the contributions from this dissertation to design research. There are a lot of benefits to having the *design string* elements for data analysis. The next chapter will highlight the types of analysis the *design string* provides for the data from the design journals.

Chapter 5: Student Design Study (1-3) Results

This chapter presents the results from the three Student Design Studies during which students recorded in design journals throughout their capstone design course. First (Section 5.1) is a look inside the design journals that highlights the content of the records that the students made. The results from the three studies are presented separately because they were each administered differently. Second (Section 5.2) describes which cognitive activities were found in the design journals. This section highlights the cognitive activities by class and also by design phase. In Section 5.3 team concept development results are given using the concept coding metrics presented in the previous chapter. In Section 5.4 visual representations found in the design journals are presented. In Section 5.5 differences within Student Design Study 2 are observed between students using traditional design journals and the students using the Smartpen technology. Finally, Section 5.6 presents the qualitative data obtained from exit interviews that the students participated in after the completion of their design journals relating to their design journaling experiences.

5.1 Inside the Design Journals

This section goes inside the design journal content from the students' detailed records. The design journals included a vast amount if information about the students' design experiences. The amount of journaling activity can be measured by the design sessions and design segments which result in the activity density.

5.1.1 Student Design Study 1- Individual Study

Student Design Study 1 is composed of two groups- Team Study (N=10) and Individual Study (N=5). This section will present the results from the Individual Study group. This pilot study effort was done with the purpose of capturing the design activities that occur during the conceptual design phase. Detailed information about the students in this study is shown in Table 22, including design journal activity density. All students in Student Design Study 1 (Individual Study) were given a traditional design journal (11.75x9.25) with 152 pages. The length of the study was 4-6 weeks depending on when the students were given their design journals.

Table 22: Student Design Study 1 (Individual Study) Detailed Subject Information

Student Design Study 1 (Individual Study) Detailed Information				
Student	*Team Project*	*Team Size*	*Journal Pages Used*	*Activity Density*
1	The Natural Born Griller	6	9	9
2	A Stable Walker for Stairs	6	14	4.87
3	Automated Window Control System	6	34	4.67
4	Napkin Set Roller	4	15	2.67
5	Automatic Egg Cooker	7	7	2
Average		5.8	15.8	5.3
Standard Deviation		1.09	10.70	3.30

The Individual Study design journals included 59 design sessions averaging 12 sessions for each student. The number of design segments was 253 averaging 51 segments per student. The total number of journal pages used was 79 with the average being 15.8 pages used per student. Inserted pages were found in the design journals, 34 to be exact. The average number of journal entries written by hand is 43%. The numbers of dated sessions are 49 or 63%. Table 23 shows the number of design sessions with the number of design segments, and the variation shown is expected.

This comparison shows the difference in the number of cognitive activities that can be found in the design sessions. It is expected that the number of design segments will be higher than the number of design sessions.

Table 23: Student Design Study 1 (Individual Study) Number of Design Sessions and Design Segments

Student Design Study 1 (Individual Study) Design Sessions and Design Segments		
Student	*Design Sessions*	*Design Segments*
1	4	36
2	15	73
3	21	98
4	12	32
5	7	14
Average	11.8	50.6
Standard Deviation	6.68	34.08

The design phase segment coding results are shown in Table 24 for the students in the Individual Study group from Student Design Study 1. It is not surprising that the majority of the design journal entries were made during the concept generation phase because this study was meant to capture that specific phase. The students who wrote journal 4 and journal 5 were probably moving faster in the design process than the pace that is set for the class. Although the instructors plan the course for the students to progress at a certain pace often times the students will often initiate a change in design phase especially in circumstances where they are progressing rapidly.

Table 24: Student Design Study 1 (Individual Study) Design Phase Percents

Student Design Study 1 (Individual Study) Relative Activity per Design Phase					
Student	*Conceptual Design*	*Embodiment*	*Detail Design*	*Redesign*	*Unknown*
1	89%	0%	0%	0%	11%
2	90%	8%	0%	0%	1%
3	46%	5%	3%	0%	46%
4	28%	63%	0%	3%	6%
5	14%	71%	0%	0%	14%

5.1.2 Student Design Study 1- Team Study

Student Design Study 1 also included a Team Study (N=10). The students in this group were from two intact teams and participated in the pilot study for the entire semester as a course requirement. This section will present the results from the Team Study group. Detailed information about the students in this study group is shown in Table 25, including design journal activity density. All students in Student Design Study 1 (Team Study) were given a traditional paper-bound design journal (8.5x11) with 96 pages. The length of the study was the entire 15-week semester and the team size was 5 members each.

Table 25: Student Design Study 1 (Team Study) Detailed Subject Information

Student Design Study 1 (Team Study) Detailed Information			
Student	*Team Project*	*Journal Pages Used*	*Activity Density*
1	Helicopter Simulator	33	3.48
2	Helicopter Simulator	14	2.89
3	Helicopter Simulator	23	6.11
4	Helicopter Simulator	19	4.55
5	Helicopter Simulator	25	4.15
1	Tiny Microphone Stands	9	3.91
2	Tiny Microphone Stands	20	6.67
3	Tiny Microphone Stands	38	7.05
4	Tiny Microphone Stands	16	3.88
5	Tiny Microphone Stands	66	4.94
Average		26.3	4.47
Standard Deviation		16.39	2.055

The students in the Team Study were on two teams with 5 members working on the projects listed in Table 25. The Team Study design journals resulted in 164 design sessions averaging 16 sessions per student. The total number of design segments is 800 averaging 80 design segments per student design journal. The total number of journal pages used is 263 with the average student using 26.3 pages. It was found that students inserted loose papers into the design journal using tape or staplers;

55 such pages were found in the Team Study journals. This means that of the 263 pages used in the design journals 79% were actually written by hand. The design journal guidelines required that the students date each session and it was found that only 55% of the session were actually dated.

A table of the segments and sessions by student is shown in Table 26. This is similar to the Individual Study in that the number of design segments is going to be higher than the number of design sessions, which is considered normal.

Table 26: Student Design Study 1 (Team Study) Design Sessions and Design Segments

Student Design Study 1 (Team Study) Design Sessions and Design Segments			
	Student	*Design Sessions*	*Design Segments*
Team 1	1	23	80
	2	9	26
	3	18	110
	4	11	50
	5	20	83
Team 2	1	11	43
	2	12	80
	3	19	134
	4	8	31
	5	33	163
	Average	16.4	80
	Standard Deviation	7.77	45.0

Table 27 shows the design phase results by percent of design segment for Team Study group from Student Design Study 1. The students in the Team Study were using the design journals the entire semester hence it is expected that more variation between the design phases should be found. The journal coding process was still being developed when these design journals were coded and that can explain the high amount of entries in the "Unknown" category.

Table 27: Student Design Study 1 (Team Study) Design Phase Percents

Student Design Study 1 (Team Study) Relative Activity per Design Phase						
	Student	*Conceptual Design*	*Embodiment*	*Detail Design*	*Redesign*	*Unknown*
Team 1	1	21%	38%	14%	0%	28%
	2	38%	27%	8%	0%	27%
	3	22%	21%	1%	0%	56%
	4	28%	30%	0%	0%	42%
	5	17%	16%	0%	0%	67%
Team 2	1	21%	38%	14%	0%	37%
	2	38%	27%	8%	0%	16%
	3	22%	21%	1%	0%	23%
	4	28%	30%	0%	0%	10%
	5	17%	16%	0%	0%	25%

It is not surprising that the majority of the design journal entries were made during the concept generation phase. The students in Student Design Study 1 (Team Study) were given a homework assignment early in the semester that required them to make conceptual design sketches using their design journals. The homework assignment given by the instructor (Dr. Linda Schmidt) is shown in Figure 30.

Select the top three concepts among those you have contributed to your team and perform the following for each concept sketch (please devote one full page to each concept):

1. *Clean up the sketch to make sure all parts of the design are represented clearly, showing the device from as many views as necessary to describe its features and operation. Designs that are only small deviations from earlier sketches in the homework are not acceptable.*
2. *Name, number and label each physical feature.*
3. *Write a short description of your proposed device and how it functions. Use the feature numbers and names from step 2 in your description (an example is provided below).*
4. *Identify three strengths and three weaknesses of the design*

NOTE: CAD DRAWINGS ARE NOT ACCEPTABLE FOR THIS ASSIGNMENT. YOU MUST PROVIDE YOUR HAND SKETCHES, WHICH ARE AN INTEGRAL PART OFTHE DESIGN PROCESS.

Figure 30: Conceptual Design Homework Assignment

5.1.3 Student Design Study 2

This section will present the results from the Student Design Study 2. This second study was done with the purpose of capturing the design activities that occur during the embodiment design phase and also to look at the differences between using a traditional design journal and a new Smartpen technology. Detailed information about the students in this study is shown in Table 28. The time period (5 weeks) for this study was actually weeks 5-10 of the 15 week semester and all the participants were in the study for the same amount of time. This is when the students should have been leaving the conceptual design phase and entering into the embodiment design phase according to the course plan. All students in this study were on teams that had 5 team members.

Table 28: Student Design Study 2 Detailed Subject Information

Student Study 2 Subject Information						
Student	*Team Project*	*Journal Type*	*# of Journal Pages*	*Design Sessions*	*Design Segments*	*Activity Density*
1	Team WeCycle: the benny (Bicycle-Powered Mobile Device Charger)	Pulse Smartpen (50 sheets, 6X8 size pages)	11	5	33	6.6
2	Team Injection Infection Rejection: SteriLatch Syringe	Pulse Smartpen (50 sheets, 6X8 size pages)	15	12	80	6.6
3	Team WeCycle: the benny (Bicycle-Powered Mobile Device Charger)	Traditional Design Journal (96 pages, 81/2X11 size)	13	8	85	10.63
4	Team Injection Infection Rejection: SteriLatch Syringe	Traditional Design Journal (96 pages, 81/2X11 size)	22	11	125	11.36
Average				9	81	8.79
Standard Deviation				3.16	37.66	2.55

The Student Design Study 2 design journals included 36 design sessions averaging 9 sessions per student. The number of design segments was 323 averaging 81 segments per student. The total number of journal pages used was 89 with the average being 22 pages used per student. No inserted pages were found in the design journals. All the journal entries were written by hand. The numbers of dated sessions are 24 or 67%.

The design phase segment coding results are shown in Table 29 for the students in Student Design Study 2.

Table 29: Student Design Study 2 Design Phase Percents

Student Design Study 2 Relative Activity per Design Phase				
Student	*Conceptual Design*	*Embodiment*	*Detail Design*	*Redesign*
1	0%	100%	0%	0%
2	0%	100%	0%	0%
3	0%	100%	0%	0%
4	4%	15%	70%	11%

Table 29 shows that the students were going through the embodiment phase of the design process. This shows that the students were on-track with the course timeline for their design project with the exception of student 4 who was well into the detailed design phase. Students in the capstone design course are encouraged to practice each phase of the design process yet the reality is that some move faster than others and some do not follow the course protocol altogether.

5.1.4 Student Design Study 3

This section will present the results from the Student Design Study 3. This third study effort was done with the purpose of capturing design activities throughout the entire design process, which is 15 weeks long. Detailed information about the students in this study is shown in Table 30.

Table 30: Student Design Study 3 Detailed Subject Information

Student Study 3 Subject Information				
Student	***Team Project***	***Team Size***	***Number of Journal Pages Recorded***	***Time in Study***
1	Team Road House (Modified Rowing System for Boats)	6	29	15 Weeks
2	Team Eco PowerTent (Solar Powered Tent)	5	0	3 Weeks- √
3	Team Accurate (Dynamic Coring System)	5	32	15 Weeks
4	Team Innovative Military Advancement (Unmanned Aerial Vehicle Landing Pad)	6	2	2 Weeks- √
5	Team Accurate (Dynamic Coring System)	5	28	15 Weeks
6	Team Accurate (Dynamic Coring System)	5	20	15 Weeks
7	Team Accurate (Dynamic Coring System)	5	20	15 Weeks
8	Team Eco PowerTent (Solar Powered Tent)	5	1	3 Weeks- √
9	Team Eco PowerTent (Solar Powered Tent)	5	39	15 Weeks
10	Team Barracuda Innovations (Energy Harvesting from Walking)	6	17	15 Weeks
11	Team GFU (Portable Breathalyzer with IPhone App)	5	2	7 Weeks- √
12	Team SAE ++ (Welding Rod Feeder)	7	3	6 Weeks- √
13	Team Generic (Sustainable Temperature Control for Greenhouses)	7	10	8 Weeks- √
14	Team Lockdown (Remote House Lockdown)	4	59	15 Weeks
15	Team Barracuda Innovations (Energy Harvesting from Walking)	6	19	15 Weeks

Several students did not participate for the entire 15 weeks. These students are noted in Table 30 with the √. Their reasons for leaving the study are given below:

- Student 2 noted that he simply did not want to participate in the design journal study during the 3rd week.
- Student 4 noted that he kept leaving his journal at home and also that he felt that it was redundant to write in the journal because he writes on his Ipad during class and lab. Two weeks in a row he forgot the design journal at home therefore it was not checked during the lab session as required. He commented that he tried to do both but was not able to so he decided to withdraw from participating in the study.
- Student 8 noted that he did not have time for the design journal and it would be best for him to withdraw from the study.
- Student 13 was asked to leave the study after not producing his journal 3 weeks in a row for the required check during the lab session.
- Student 11 noted that he was struggling to remember to write in the journal during week 6 and kept promising to add more, but finally decided during week 7 to no longer participate in the study.

- Student 12 noted during week 6 that he did not think he would be able to do a good job writing in the journal and asked to withdraw from participating in the study.

The Student Design Study 3 design journals included 154 design sessions averaging 17 sessions per student. The students were explicitly requested to date their design journal sessions and the results presented here only includes sessions that were dated. The number of design segments was 1032 averaging 115 segments per student. The total number of journal pages used was 264 with the average being 29 pages used per student. Inserted pages were found in the design journals, 55 to be exact. The average number of journal entries written by hand is 23. The numbers of dated sessions are 150 or 97%. Student specific information about the students in this study is shown in Table 31.

Table 31: Student Design Study 3-Detailed Subject Information

Journal	*Design Sessions (Dated)*	*Design Segments (Dated)*	*Activity Density (Dated)*	*Design Sessions Undated*	*Design Segments Undated*
1	12	76	6.33	1	23
3	20	69	3.45	0	0
5	11	123	11.18	0	0
6	20	101	5.05	1	2
7	9	119	13.22	0	0
9	33	141	4.27	0	0
10	4	48	12.00	0	0
14	26	213	8.19	1	1
15	15	110	7.33	1	6
Average	16.66	111.11	7.89	0.44	3.56
Standard Deviation	9.02	48.18	3.53	0.53	7.55

Table 32 compares the number of design sessions with the number of design segments and the variation shown is expected. The variation in activity density shows that the some students were focusing on a few cognitive activities per design session while others were not. This could mean that students with lower activity densities were writing about a specific topic or had a narrower focus during some of their design sessions. The students with higher activity densities were recording a wider range of cognitive activities each time they sat for a design session. This could also be explained by student differences in how they work.

Table 32: Student Design Study 3 Design Sessions and Design Segments

Student Design Study 3 Design Sessions and Design Segments		
Student	*Design Sessions*	*Design Segments*
1	12	76
3	20	69
5	11	123
6	20	101
7	9	119
9	33	141
10	4	48
14	26	213
15	15	110
Average	16.6	111.1
Standard Deviation	9.02	48.1

The design phase segment coding results are shown in Table 33 for the students in Student Design Study 3.

Table 33: Student Design Study 3 Design Phase Percents

Student Design Study 3 Relative Activity per Design Phase				
Student	*Conceptual Design*	*Embodiment*	*Detail Design*	*Redesign*
1	51%	16%	33%	0%
3	72%	26%	0%	1%
5	50%	50%	0%	0%
6	64%	36%	0%	0%
7	49%	51%	0%	0%
9	30%	67%	2%	0%
10	100%	0%	0%	0%
14	36%	35%	30%	0%
15	38%	45%	17%	0%

5.1.5 Design Segment per Design Phase

ANOVA was used to examine the design segments per design phase between the two teams in Student Design Study 1 (Team Study) to see if any statistically significant differences exist. The data used in this ANOVA calculation is shown in Table 34.

Table 34: Student Design Study 1 (Team Study) Design Phase Data

Percent of Journal Segments by Design Phase on Two Teams from Student Design Study 1					
Team	*Unknown*	*Conceptual Design*	*Embodiment*	*Detailed Design*	*Redesign*
Team 1	27.50%	21.25%	37.50%	13.75%	0.00%
Team 1	26.92%	38.46%	26.92%	7.69%	0.00%
Team 1	56.36%	21.82%	20.91%	0.91%	0.00%
Team 1	42.00%	28.00%	30.00%	0.00%	0.00%
Team 1	67.47%	16.87%	15.66%	0.00%	0.00%
Team 2	37.21%	58.14%	4.65%	0.00%	0.00%
Team 2	16.25%	81.25%	1.25%	1.25%	0.00%
Team 2	23.13%	54.48%	22.39%	0.00%	0.00%
Team 2	9.68%	58.06%	32.26%	0.00%	0.00%
Team 2	25.15%	62.58%	11.04%	1.23%	0.00%

Table 35: Student Design Study 1 (Team Study) ANOVA Design Phase Results by Team

ANOVA Results			
Design Phase	*F*	*P-Value*	
Unknown	5.58	0.046	Significant
Conceptual Design	38.57	0.000	Significant
Embodiment	2.99	0.122	
Detail Design	2.09	0.186	
Re-Design	n/a	n/a	

The results from the ANOVA are shown in Table 35. The p-value significance level is below 0.05. When the p-value is below the designated level, the null hypothesis (that the team members' recording of segments in each design phase is the same) will be rejected. The results show that the amount of activity in the "unknown" and "conceptual design" phases have significant differences between the two teams. The "unknown" in this study accounted for segments where the design phase could not specifically be identified out of context with the rest of the segments. The differences are present because of the variety in the amount of design segments that fell into this category. The differences between the teams in the "conceptual design" phase can be explained by student differences in journaling behavior. The table also shows that "embodiment" and "detailed design" activity levels show have no significant differences between the groups.

ANOVA was done again to include a team from Student Design Study 3. Student Design Study 3 was not set up as a team study but 4 of the students (from a 5-person team) happened to be on the same team. Data from the 4 members of this team are added to the two teams from Student Design Study 1 (Team Study) to see if there are statistically significant differences between the design activities in each design phase for these three teams. The main difference between these groups is that the students in Student Design Study 1 were required to keep the journals for a course grade and the students in Student Design Study 3 were volunteers. Students in both studies recorded in their design journals for the entire semester. The data used for this analysis is shown below in Table 36 which is percent of design segments per design phase.

Table 36: ANOVA on Teams from Student Design Study 1 and Student Design Study 3

Percent of Journal Segments by Design Phase on Two Teams from Student Design Study 1 and One Team from Student Design Study 3					
Team	*Unknown*	*Conceptual Design*	*Embodiment*	*Detailed Design*	*Re-Design*
Team 1	27.50%	21.25%	37.50%	13.75%	0.00%
Team 1	26.92%	38.46%	26.92%	7.69%	0.00%
Team 1	56.36%	21.82%	20.91%	0.91%	0.00%
Team 1	42.00%	28.00%	30.00%	0.00%	0.00%
Team 1	67.47%	16.87%	15.66%	0.00%	0.00%
Team 2	37.21%	58.14%	4.65%	0.00%	0.00%
Team 2	16.25%	81.25%	1.25%	1.25%	0.00%
Team 2	23.13%	54.48%	22.39%	0.00%	0.00%
Team 2	9.68%	58.06%	32.26%	0.00%	0.00%
Team 2	25.15%	62.58%	11.04%	1.23%	0.00%
Team 3	0%	72%	26%	0%	1%
Team 3	0%	50%	50%	0%	0%
Team 3	0%	64%	36%	0%	0%
Team 3	0%	49%	51%	0%	0%

The results from the ANOVA are shown in Table 37. There are significant differences between “unknown”, “conceptual design”, and “embodiment” design phases. It is important to note that the design journal coding process was still evolving when Student Design Study 1 journals were coded; this is why the “unknown” category was included. This explains the reason for the significant difference for that category. The other design phases with significant differences are “conceptual design” and “embodiment” which could mean that the student’s uses for the journals were different at these stages and not for the last two stages of the design process. These resulting differences could also be a result of the differences in student motivation to use the design journal. The students in Student Design Study 1 were required and the students in Student Design Study 3 were all volunteers.

Table 37: Student Design Study 1 (Team Study) and Student Design Study 3 ANOVA Results on Design Phase Activity by Team

ANOVA Results			
Design Phase	*F*	*P-Value*	
Unknown	14.01	0.001	Significant
Conceptual Design	20.46	0.000	Significant
Embodiment	6.21	0.016	Significant
Detailed Design	2.08	0.171	
Re-Design	1.31	0.309	

5.1.6 Activity Density per Design Journal

Another metric useful for identifying differences in journaling behavior is activity density. For the first ANOVA comparison, the group from Dr. Sobek's design journal study will be used to compare activity densities with Student Design Study 1 (Team Study). The students in Student Design Study 1 and Dr. Sobek's design study team used the design journals as a requirement for a course grade. The data used for this ANOVA test is shown in Table 38.

Table 38: ANOVA on Activity Density between Dr. Sobek's Team and Student Design Study 1 (Team Study)

ANOVA on Activity Density from Dr. Sobek's Team and Student Design Study 1 (Team Study)		
Team Sobek	*Team 1*	*Team 2*
6.6	3.48	3.91
10.625	2.89	6.67
11.364	6.11	7.05
	4.55	3.88
	4.15	4.94

The results yield a p-value (0.004) that is below 0.05 which means that there is a statistically significant difference between the activity densities of the students in these studies. A difference in activity density shows the journal writers' variances in amount of cognitive activities per design session. These results show that differences in administration (detailed in Chapter 3) may have an effect on the journal records.

ANOVA was also done on the activity densities of the individual students participating in the three studies for this dissertation. The data used for this ANOVA test is shown in Table 39.

It is not surprising that the results gave a p-value (0.005) that is below 0.05. There is a statistically significant difference between the activity densities of the students in these studies. The administration and goals for each of these studies were different so it is not expected that the journaling behavior observed would be the same. The average activity densities are higher for Student Design Study 2 and Student Design Study 3. Student Design Study 3 journaled for a longer period of time which could explain why they have a higher average activity density. Student Design Study 2 has almost a 50/50 split between the journalers' activity densities, this is probably because 2 students were using traditional design journals and 2 students were using the Smartpen technology. This can explain the difference that is seen here.

Table 39: Activity Density for Student Design Study 1, Student Design Study 2, and Student Design Study 3

	Average Activity Density		
	Student Design Study 1	Student Design Study 2	Student Design Study 3
	3.48	6.6	6.33
	2.89	6.6	3.45
	6.11	10.63	11.18
	4.55	11.36	5.05
	4.15		13.22
	3.91		4.27
	6.67		12
	7.05		8.19
	3.88		7.33
	4.94		
	9		
	4.87		
	4.67		
	2.67		
	2		
Average	4.811429	8.7975	7.891111
Standard Deviation	2.19919	2.554896	3.532809

5.1.7 Inserts per Design Journal

It was expected that the students would use the journals to perform their work on project tasks (e.g., sketching concepts, summarizing information from websites, perform simple calculations of forces). It was surprising that some students used their journals as only a collection folder for other documents created using a computer. Some of the types of collection documents found in the students design journals were CAD drawings, g-chat conversation logs, handouts given by the professor, drafts or parts of drafts of the final design report, line drawings made on the computer, bill of materials, and engineering drawings. These documents were cut from other sources and taped into the design journals.

ANOVA was done on the number of inserts by the individual students participating in the three studies for this dissertation. The data used for this ANOVA test is shown in Table 40.

Table 40: Number of Journal Inserts per Student

	Number of Journal Inserts		
	Student Design Study 1	Student Design Study 2	Student Design Study 3
	20	0	9
	11	0	0
	0	0	0
	6	0	0
	8		9
	2		22
	8		5
	27		4
	3		4
	72		
	1		
	1		
	33		
	4		
	0		
Average	12.57143	0	5.888889
Standard Deviation	19.37033	0	6.990072

It is not surprising that the results gave a p-value (0.24) that is above 0.05 which means that there is no statistically significant difference between the numbers of inserts of the students in these studies. These are not surprising results because using inserts in a design journal seem to be a matter of varying preference for students in the studies. There were many more inserts in Study 1 when the protocol for monitoring the journals was new. The weekly monitoring in Study coincided with a much lower instance of adding inserts to the journals.

5.2 Cognitive Activities

5.2.1 Cognitive Codes

Student Design Study 3 students cognitive coding results are given in this section. Each journal in Student Design Study 3 was coded with the cognitive coding scheme (36 codes) presented in Chapter 3. On the following pages a chart is created for each student showing the relative distribution of segments in their journal by cognitive code. The data was expanded by code class see how the students were using the journals. The resulting charts by class appear as Figure 69 through Figure 77 that can be found in the appendix.

The majority of the students appear to have a good representation of the classes across their design journals. Journal 1 and Journal 3 show noteworthy differences. It appears that they used the journal to describe only one or two cognitive activities.

- The highest code for Journal 1was is “other” which was 26% of the journal entries. Segments found in Journal 1 that were coded other include unfinished text, instructions for the journal reader to unfold a page, table of contents, and unfinished text that was scratched out. Journal 1 included 99 design segments (hence about 26) coded as “no evidence of cognitive activity” in this design journal.
- Journal 3 spent 65% of their time on project ideas which means that they clearly did not understand the uses of a design journal and missed out on some of the benefits that were possible.

Table 41: Code Results for Student Design Study 3 by Class

	1	3	5	6	7	9	10	14	15
Search	0%	0%	0%	0%	0.84%	1.42%	0%	3.27%	0%
References	1.01%	0%	13.82%	0%	0%	12.77%	0%	13.55%	13.79%
Questioning	2.02%	4.35%	2.44%	3.88%	0%	2.84%	0%	5.61%	0.86%
Price Quotes	0%	0%	0%	0%	0.84%	0%	0%	0%	0%
Definitions	0%	0%	0%	0%	0%	0%	0%	0.47%	6.03%
Customer Requirements	0%	1.45%	3.25%	2.91%	3.36%	2.84%	0%	10.28%	0.86%
PS Clarification	5.05%	1.45%	1.63%	0%	2.52%	1.42%	0%	1.40%	7.76%
Criteria List	1.01%	0%	0.81%	0%	7.56%	0%	0%	0%	0%
Engineering Characteristics	0%	0%	4.88%	0%	0%	3.55%	0%	0%	0%
Project Ideas	12.1%	65.2%	29.2%	61.1%	53.78%	17.02%	58.%	1.40%	34.48%
Analogical Reasoning	1.01%	0%	0%	0%	0%	0%	12.5%	1.40%	2.59%
Material Options	1.01%	7.25%	0%	1.94%	0%	0%	0%	0.47%	1.72%
Estimates	0%	0%	0%	0%	0%	0%	0%	0%	0%
Assumptions	2.02%	0%	0%	0%	0%	0%	2.08%	0%	0%
Calculations	0%	1.45%	2.44%	0.97%	0.84%	0%	20.8%	1.40%	6.90%
Testing Procedures	1.01%	5.80%	9.76%	5.83%	1.68%	6.38%	0%	1.87%	1.72%
Variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
Explanations	0%	0%	5.69%	5.83%	0%	0%	0%	0.47%	0%
Recommendations	1.01%	0%	0%	4.85%	0%	0%	0%	3.27%	0%
Conclusions	4.04%	0%	6.50%	5.83%	5.04%	2.84%	0%	0%	8.62%
Design Changes	0%	0%	0%	0%	0%	0%	0%	1.87%	0%
To Do Lists	1.01%	10.14%	7.32%	0.97%	1.68%	21.99%	0%	5.61%	2.59%
Meeting Notes	0%	0%	0%	0%	0%	3.55%	2.08%	0%	0%
Task Assignments	1.01%	0%	0%	0%	0%	11.35%	2.08%	3.27%	1.72%
Inventory	1.01%	0%	0%	0%	0%	0.71%	0%	0%	0%
Task Completion	1.01%	0%	0%	0%	0%	4.26%	0%	0%	0%
Project Milestones	1.01%	0%	0%	0%	0.84%	0.71%	0%	0%	0%
Field Trip Notes	0%	0%	0%	0%	0%	0%	0%	0%	0%
Personal Notes	13.13%	0%	0%	2.91%	1.68%	0%	0%	3.74%	0%
Design Process Notes	4.04%	0%	0%	0.97%	0%	0%	0%	0%	0%
Revelations	18.18%	0%	0%	0.97%	0%	0%	0%	0.47%	0.86%
Mistakes	0%	0%	0%	0%	0%	0%	0%	0%	0%
Cross References	1.01%	0%	0%	0%	2.52%	0%	0%	0%	0%
Illegible Entries	0%	0%	1.63%	0%	2.52%	0%	0%	0.93%	0%
Designer Signature	1.01%	0%	0%	0%	0%	0%	0%	0.93%	0%
None	26.26%	2.90%	8.94%	0.97%	14.29%	6.38%	2.08%	7.48%	9.48%

5.2.2 Information Seeking and Noting Cognitive Class

The information seeking and noting cognitive class results are shown in Table 42. These results show that the students were using information seeking and noting class codes and at least 4 of them almost at 20% of the journal entries belong to this class. *References* seem to have the highest activity in this class. References are important for the student's design projects at all stages to aid in decision making. Not many students used *Price Quotes* which is not surprising because the budget for the course is only $250 per team so this is not something that the students would spend a significant amount of time dealing with. Also *Definitions* are pretty low with the exception of Student 15.

Table 42: Code Results for Information Seeking and Noting Class (See Table 11)

	Search	References	Questioning	Price Quotes	Definitions	Total
Student 1	0%	1.01%	2.02%	0%	0%	3%
Student 3	0%	0%	4.35%	0%	0%	4%
Student 5	0%	13.82%	2.44%	0%	0%	16%
Student 6	0%	0%	3.88%	0%	0%	4%
Student 7	0.84%	0%	0%	0.84%	0%	2%
Student 9	1.42%	12.77%	2.84%	0%	0%	17%
Student 10	0%	0%	0%	0%	0%	0%
Student 14	3.27%	13.55%	5.61%	0%	0.47%	23%
Student 15	0%	13.79%	0.86%	0%	6.03%	21%
Average	1%	6%	2%	0%	1%	
Standard Deviation	0.01119	0.070131	0.019529	0.0028	0.019965	

5.2.3 Problem Understanding Cognitive Class

The problem understanding cognitive class results are shown in Table 43. Understanding the design problem is a pivotal part of the design process because once the problem is well understood by the team members they can proceed to toward a suitable solution to the problem. *Customer Requirements* are seen in all but two of the journals. This is not surprising because the course requires that students understand the consumer of the design that they are making. Marketing research and analysis and ethnographic studies are encouraged in the capstone design course. It was expected that *Engineering Characteristics* would have appeared more in these design journals because of the course requirement to make a House of Quality that includes an engineering characteristics room. Only 3 students had engineering characteristics entries in their design journals. *Problem Statement Clarification* cognitive codes are found in all but 2 of the students design journals.

Table 43: Code Results for Problem Understanding Class (See Table 11)

	Customer Requirements	Problem Statement Clarification	Criteria List	Engineering Characteristics	Total
Student 1	0%	5.05%	1.01%	0%	6%
Student 3	1.45%	1.45%	0%	0%	3%
Student 5	3.25%	1.63%	0.81%	4.88%	11%
Student 6	2.91%	0%	0%	0%	3%
Student 7	3.36%	2.52%	7.56%	0%	13%
Student 9	2.84%	1.42%	0%	3.55%	8%
Student 10	0%	0%	0%	0%	0%
Student 14	10.28%	1.40%	0%	0%	12%
Student 15	0.86%	7.76%	0%	0%	9%
Average	3%	2%	1%	1%	
Standard Deviation	0.031173	0.025181	0.024762	0.018881	

5.2.4 Idea Generation Cognitive Class

The idea generation cognitive class results are shown in Table 44. This was the most popular category among the journal writers. *Project Idea* code was found the most out of all the 36 cognitive codes in the students design journals. The students have a place to document their creativity and also can use the design journal records to convince and explain their ideas to their team members. Three of the students had over 50% of their journal entries that belong to the *Project Idea* cognitive code. *Analogical Reasoning* was seen only in about half of the students design journals and then where it did appear in low numbers. This is a surprising result because it was thought that the students would do more of this type of cognitive activity during the design process. The cognitive code *Material Options* is seen in most of the students design journals.

Table 44: Code Results for Idea Generation Class (See Table 11)

	Project Ideas	Analogical Reasoning	Material Options	Total
Student 1	12.12%	1.01%	1.01%	14.14%
Student 3	65.22%	0%	7.25%	72.47%
Student 5	29.27%	0%	0%	29.27%
Student 6	61.17%	0%	1.94%	63.11%
Student 7	53.78%	0%	0%	53.78%
Student 9	17.02%	0%	0%	17.02%
Student 10	58.33%	12.50%	0%	70.83%
Student 14	1.40%	1.40%	0.47%	3.27%
Student 15	34.48%	2.59%	1.72%	38.79%
Average	36.98%	1.94%	1.38%	
Standard Deviation	0.236346	0.040606	0.02331	

5.2.5 Analysis Cognitive Class

The analysis cognitive class results are shown in Table 45. The analysis class is one of the largest cognitive classes with 6 cognitive codes. The cognitive codes *Estimates* and *Variables* were not used at all in these students design journals. The short time of the design course probably is the reason we did not get to see any of those codes in the design journals. *Calculations* were found in majority of the students design journals, this was expected because of the importance of different types of calculations in the design process. The students are required to include a section in their final design report on testing with results so it was expected that we would find this code in the design journals. All the students but one had a segment coded *Testing Procedures.*

Table 45: Code Results for Analysis Class (See Table 11)

	Estimates	Assumptions	Calculations	Testing Procedures	Variables	Explanations	Total
Student 1	0%	2.02%	0%	1.01%	0%	0%	3%
Student 3	0%	0%	1.45%	5.80%	0%	0%	7%
Student 5	0%	0%	2.44%	9.76%	0%	5.69%	18%
Student 6	0%	0%	0.97%	5.83%	0%	5.83%	13%
Student 7	0%	0%	0.84%	1.68%	0%	0%	3%
Student 9	0%	0%	0%	6.38%	0%	0%	6%
Student 10	0%	2.08%	20.83%	0%	0%	0%	23%
Student 14	0%	0%	1.40%	1.87%	0%	0.47%	4%
Student 15	0%	0%	6.90%	1.72%	0%	0%	9%
Average	0%	0%	4%	4%	0%	1%	
Standard Deviation	0	0.009041	0.06693	0.032609	0	0.025153	

5.2.6 Decisions Cognitive Class

The decisions cognitive class results are shown in Table 46. It was important to show that the students are making and recording decisions that they make in the design journals. The students have to use their previous knowledge and other resources to make choices about materials, sizes, shapes, and other factors needed for their design project. The codes *Recommendations* and *Design Changes* did not occur that many times in the students design journals.

Table 46: Code Results for Decisions Class (See Table 11)

	Recommendations	Conclusions	Design Changes	Total
Student 1	1.01%	4.04%	0%	5.05%
Student 3	0%	0%	0%	0.00%
Student 5	0%	6.50%	0%	6.50%
Student 6	4.85%	5.83%	0%	10.68%
Student 7	0%	5.04%	0%	5.04%
Student 9	0%	2.84%	0%	2.84%
Student 10	0%	0%	0%	0.00%
Student 14	3.27%	0%	1.87%	5.14%
Student 15	0%	8.62%	0%	8.62%
Average	1.01%	3.65%	0.21%	
Standard Deviation	0.018019	0.031679	0.006233	

5.2.7 Project Management Cognitive Class

The project management cognitive class results are shown in Table 47. Project management was clearly not important for the students in this design study. Student 1 and Student 9 were the only two that consistently had codes related to project management. Student 9 was clearly the project manager or team leader for their team. Senior design students have a heavy course load and could have used the design journal as a place for just the design project notes if they were not in charge of managing the design team. The professors encourage the students to rotate the team manager but sometimes it ends up being the same students for the majority of the semester. Also sometimes when a student is naturally talented in leadership and organization skills they will volunteer to be the team leader for the group for the entire semester.

Table 47: Code Results for Project Management Class (See Table 11)

Student Number	To Do Lists	Meeting Notes	Task Assign-ments	Invent-ory	Task Comp-letion	Project Milesto nes	Field Trip Notes	Total
1	1.01%	0%	1.01%	1.01%	1.01%	1.01%	0%	5.05%
3	10.14%	0%	0%	0%	0%	0%	0%	10.14%
5	7.32%	0%	0%	0%	0%	0%	0%	7.32%
6	0.97%	0%	0%	0%	0%	0%	0%	0.97%
7	1.68%	0%	0%	0%	0%	0.84%	0%	2.52%
9	21.99%	3.55%	11.35%	0.71%	4.26%	0.71%	0%	42.57%
10	0%	2.08%	2.08%	0%	0%	0%	0%	4.16%
14	5.61%	0%	3.27%	0%	0%	0%	0%	8.88%
15	2.59%	0%	1.72%	0%	0%	0%	0%	4.31%
Average	5.70%	0.63%	2.16%	0.19%	0.59%	0.28%	0.00 %	
Std. Dev.	0.069857	0.012946	0.036379	0.003866	0.014178	0.004332	0	

5.2.8 Reflection Cognitive Class

The reflection cognitive class results are shown in Table 48. Reflections are important because they show some level of metacognition from the student. One example of reflection found in Student 1's journal was a note about the way that the teams were formed at the beginning of the course and how the other thought about how they choose their group. This same student also later noted that they were not excited about the group they ended up working with or the design project itself. It is important to note that the student also said that despite his feelings he was going to put forth the best effort he could.

Table 48: Code Results for Reflection Class (See Table 11)

	Personal Notes	Design Process Notes	Revelations	Mistakes	Cross References	Total
Student 1	13.13%	4.04%	18.18%	0%	1.01%	36.36%
Student 3	0%	0%	0%	0%	0%	0.00%
Student 5	0%	0%	0%	0%	0%	0.00%
Student 6	2.91%	0.97%	0.97%	0%	0%	4.85%
Student 7	1.68%	0%	0%	0%	2.52%	4.20%
Student 9	0%	0%	0%	0%	0%	0.00%
Student 10	0%	0%	0%	0%	0%	0.00%
Student 14	3.74%	0%	0.47%	0%	0%	4.21%
Student 15	0%	0%	0.86%	0%	0%	0.86%
Average	2.38%	0.56%	2.28%	0.00%	0.39%	
Standard Deviation	0.042794	0.013451	0.059771	0	0.00865	

5.2.9 Other Cognitive Class

The other cognitive class results are shown in Table 49. The entries in this class did not fit into any of the other classes.

Table 49: Code Results for Other Class (See Table 11)

	Illegible Entries	Designer Signature	None	Total
Student 1	0%	1.01%	26.26%	27%
Student 3	0%	0%	2.90%	3%
Student 5	1.63%	0%	8.94%	11%
Student 6	0%	0%	0.97%	1%
Student 7	2.52%	0%	14.29%	17%
Student 9	0%	0%	6.38%	6%
Student 10	0%	0%	2.08%	2%
Student 14	0.93%	0.93%	7.48%	9%
Student 15	0%	0%	9.48%	9%
Average	1%	0%	9%	
Standard Deviation	0.009357	0.004282	0.077808	

5.2.10 Design Phases

Student Design Study 3 participants use of cognitive codes in different design phases are explored in this section. The design phases for this analysis were determined by the dates of the semester specified in the course syllabus. The instructors prepare lectures and assignments around the particular design phase that students should be progressing through. For Student Design Study 3 the three design phases that are analyzed are conceptual design, embodiment design, and detailed design. Conceptual design starts on September 9, 2011. Embodiment design starts on September 29, 2011. Detailed Design starts on October 27, 2011. The design sessions used from Student Design Study 3 for this analysis are only the dated entries so a matching with the intended course design phase could be done in later analysis. Table 50 shows the results to the hypothesis presented in chapter 4 (Section 4.2.4) regarding what cognitive classes would be found the most in certain design phases.

Table 50: Design Phase Hypothesis (H1-H4) Results for Student Design Study 3

Design Phase Hypothesis for Conceptual Design			
H1: Information Seeking and Noting (1), Problem Understanding (2), and Idea Generation (3)	Greater than	All other Classes	True
Design Phase Hypothesis for Embodiment Design			
H2: Analysis (4)	Greater than	All other Classes	False
Design Phase Hypothesis for Detailed Design			
H3: Decisions (5)	Greater than	All other Classes	False
Design Phase Hypothesis for Re-Design			
H4: Reflection (7)	Greater than	All other Classes	N/A

Information seeking and noting, problem understanding, and idea generation (H1) made up 72% of the design journal entries during the conceptual design phase. Analysis (H2) only made up 10% of the design journal entries during the embodiment design phase, our hypothesis was false. Decisions (H3) only made up 6% of the design journal entries during the detailed design phase, our hypothesis was false. The students in Student Design Study 3 did not enter the re-design phase of the design process which leaves (H4) unanswered.

5.3 Concept Development

The concept referencing ratios presented in this section are proposed to highlight team participation in creating concepts, developing concepts, and presenting the final team concept. All of the proceeding are milestones the students should invest a significant amount of time in during the product development process. Although the data in the Student Design Study 1 (Individual Study) did reveal that concepts were mentioned by the students. The referencing ratios were not relevant because a collection of team journals is needed to apply the equations.

A concept is usually clearly defined by the students with the label "concept + number" (Example "Concept 1, Concept 2, etc.). The final assembly of selected or considered designs of the artifact is also considered a concept occurrence. Team concepts were coded as they appeared in the journals, which were coded in random order. All concepts were recorded even if they only appeared once across the team's journals. A concept that appeared in multiple journals across a team is best decided by the students handwriting and name (if given), where possible, to establish authorship. Unique penmanship was used to establish authorship when foreign designs occurred across teams journals in most cases. This is only possible when something written by one team member is copied into another's journal. Name was used when students referred to concepts by "final concept" or "Tony's concept #1", etc. It is expected that students are the only authors of all the design records yet where they are not they should explicitly credit the owner by citation. At times the students did not do this. One example of how different concepts were seen as occurring in students' design journals was a listing of all the teams concepts with pro's and con's commentary.

The following examples are from one of the teams in Student Design Study 1 (Team Study). An example of the results of concept coding from one of the teams in Student Design Study 1 (Team Study) is shown in Table 51. The concepts were given numbers based on the order they were found in the design journals. This made it easier to identify concepts seen across team journals. Looking at this table Concept 1 found in Design Segments 6 belongs to Student 1 from this team. The owner of the concept is the same no matter where the mention of the concept is, if found in a different design journal.

Table 51: Student Design Study (Team Study) Concept Coding Example

Concept Coding Example from Student Design Study 1 (Team Study)			
Date	*Design Segment in Journal 1*	*Concept*	*Owner*
9/16/2010	6	1	1
	7	2	1
	8	3	4
	9	4	4
	10	5	2
	11	6	2
	12	7	5
	13	8	5

In order to determine the impact of reliance on student's own journaling motivation for documentation results of the pilot study are compared with a design journal study that was done in a more controlled research environment. Data that was generously donated by Dr. Duward Sobek from Montana State University previously in the RISE 2006 Summer Research Program was coded for concepts as well [78]. The data labeled Team S was a group of 3 students at Montana State University participating in a similar senior capstone design course. Dr. Sobek had a more regimented and monitored design journal study that he closely maintained. This research's Student Design Study 1 (Team Study) setup allowed the students more freedom with journal entry content than Team S was allowed when they recorded their design journals. The design journals completed by Team S will serve as a control group for analyzing the data from one of the Team Study groups as part of the concept coding process.

Table 52 shows the results of the self, others, team, and final concept referencing ratios for one team from Student Design Study 1 (Team Study).

Table 52: Student Design Study 1 (Team Study) Concept Referencing Results

Student Design Study 1(Team Study)Concept Referencing Ratio Results				
Subject	*Self*	*Others*	*Team*	*Final*
1	27%	73%	79%	9%
2	0%	100%	7%	100%
3	60%	40%	93%	23%
4	31%	69%	21%	69%
5	16%	84%	71%	42%
Average	**27%**	**73%**	**54%**	**49%**
Sample Standard Deviation	**0.222**	**0.222**	**0.364**	**0.376**

From Table 52 it is apparent that the students on this team did not devote much time to the concepts they generated themselves, with the exception of student 3. The high number of others concept referencing shows that the students on this team were very involved in the concept selection process and felt the need to have a permanent record of all their selections of designs. The student 2 only referenced a single concept in their entire design journal. This student earned a grade of 25% on their journal for the course.

Table 53 shows the self, others, team, and final concept referencing ratios for one team from Dr. Sobek's group (Team S). Team S had 3 students whose design journals were coded for self, others, team, and final concept referencing ratios. Table 53 shows that the students in Team S recorded consistently in their design journals. The high percentages of self and team referencing ratio's shows they were actively participating in the design process while recording in their design journals.

Table 53: Dr. Sobek's Control Group Team S Concept Referencing Results

Team S Concept Referencing Ratio Results				
Subject	*Self*	*Others*	*Team*	*Final*
S1	80%	20%	50%	29%
S2	71%	29%	35%	33%
S3	64%	36%	55%	20%
Average	**72%**	**28%**	**47%**	**27%**
Sample Standard Deviation	**0.081**	**0.081**	**0.067**	**0.104**

Statistical Analysis was done on the combination of Student Design Study 1 (Team Study) Group and Team S data to find out if there were significant differences between the concept referencing ratios of the two teams. The ANOVA values are shown below in Table 54.

Table 54: ANOVA on Concept Referencing Ratios for Student Design Study 1 (Team Study) and Team S

ANOVA Results for Student Design Study 1 and Team S				
Ratio	*F-Critical*	*F- Value*	*P*	*Result*
Self CRR	5.98	10.65	0.01	Significant
Others CRR	5.98	10.65	0.01	Significant
Team CRR	5.98	0.11	0.75	
Final CRR	5.98	0.95	0.36	

The P-value ($p < 0.05$ is significant) gives the probability that the same observations would be made if the samples were taken randomly. This data set shows that there are significant differences between the $self_{CRR}$ and the $other_{CRR}$ between the two groups. This can be attributed to differences in the administration of the study and also student preferences for design journal recording. The students in Student Design Study 3 actually have higher overall values for concept references found in the design journals compared to the students on Team S. The F values show the increase or decrease in the probabilities and are inversely proportional to the p values. Meaning as the F values increase the probability decreases and vice versa, as shown in the table. This data set shows that there are no significant differences between the $team_{CRR}$ and the $final_{CRR}$ between the two groups, which is surprising due to the way in which both studies were structured.

This is validation that the concept referencing metrics can be used with student's natural journaling habits. The argument is not strong for either case, yet it is clear that a design journal study done *in situ* can show data at the same level or greater of participation by the students. The Student Design Study 1(Team Study) was conducted *in situ* meaning in the designer's natural setting, which can account for some inconsistencies in the data collected. These inconsistencies can be expected when participants' journals are not rigorously monitored and therefore are not motivated to adhere to all given guidelines.

5.4 Visual Representations in Design Documentation

Student's use of visual representations in the design journals is important for this dissertation because visuals are tools used for understanding, explaining, modeling, and creating during the design process. Visuals were found throughout all the design journals in various design phases. The usage of different types of visuals by design phase also shows more examples of the rich data and variety of records found in the design journals. First the visual codes found in each journal by percent are given in Table 55.

Table 55: Student Design Study 3 Percent of Visual Codes by Journal

Student Design Study 3 Visual Code Information									
Visual Code	*Std. 1*	*Std. 3*	*Std. 5*	*Std. 6*	*Std. 7*	*Std. 9*	*Std.10*	*Std. 14*	*Std. 15*
Sketch	4%	62%	11%	17%	33%	2%	32%	21%	26%
CAD	2%	0%	0%	0%	0%	0%	0%	0%	1%
Photo	4%	0%	0%	0%	0%	2%	0%	0%	0%
Simulation	0%	0%	0%	0%	0%	0%	0%	0%	0%
Line Drawing	1%	0%	0%	0%	0%	1%	0%	0%	0%
Electrical Drawing	0%	0%	0%	0%	0%	0%	0%	3%	0%
Chart/Table	2%	0%	3%	3%	2%	0%	0%	3%	1%
Free Body Diagram	0%	0%	0%	0%	0%	0%	0%	0%	0%
None	87%	38%	85%	81%	66%	95%	68%	72%	72%

From this table we conclude that not that many different kinds of visual representations were present in the students design journal. It is very clear that sketches are the main type of visual representations found in the students' design journal records.

5.5 Smartpen Technology

In Student Design Study 2 the students were from 2 groups and 2 of the students in the study used the Smartpen technology introduced in Chapter 3. ANOVA was done on the data in Table 56 and the results are shown in Table 57. The results show that there is not a statistically significant difference between the journaling behaviors of the students. This means that the tool used to create the design journal can be different without affecting the journaling behavior.

Table 56: Percent of Journal Segments by Design Phase for Student Design Study 2

Percent of Journal Segments by Design Phase on Two Teams from Student Design Study 2				
Team	*Conceptual Design*	*Embodiment*	*Detailed Design*	*Re-Design*
Team 1	0%	100%	0%	0%
Team 1	0%	100%	0%	0%
Team 2	0%	100%	0%	0%
Team 2	4%	15.20%	69.60%	11.20%

Table 57: ANOVA Results for Student Design Study 2

ANOVA Results		
Design Phase	*F*	*P-Value*
Conceptual Design	1.00	0.423
Embodiment	1.00	0.423
Detailed Design	1.00	0.423
Re-Design	1.00	0.423

5.6 Qualitative Results

Qualitative data on students' use and perceptions of the value of design journals were collected from each study group. The exit interview questions consisted of 11 general questions related to their design journaling experience. The 11 basic questions were developed based on 10 topics, which the author identified as topics important for exploring the student's journaling experiences. The students in this study participated in an exit interview administered by the author. The responses to these 11 questions were not surprising and provided some clarity to the author on how students feel about properly using design journals.

The following discussion is formatted based on the topics used to create the interview questions. The responses from Student Design Study 3 are given after the topic is introduced. A few of the questions spanned more than one topic where noted.

Topic 1: Understanding. This question is important for revealing the prior experiences that students have had with design journals by asking what their personal definition of a design journal. The responses from Student Design Study 3 are given in Table 58.

Table 58: Student Design Study 3 Question 9 Responses

Q9: Before participating in this study, what was your idea of a design journal?
• Just keeping a spiral notebook with all the papers in it. • A journal where all project related thoughts go. Brainstorming, scheduling, concepts, calculations, etc. • I had a general idea of what it would be. It was about what I expected. • I had figured the design journal would be more pertaining to just the steps specific to the PDP, but I found that it was being used to write just about everything pertaining to the product we developed. • My idea of the design journal was something I would be able to keep all my notes for the class in one place. • Just keeping a spiral notebook with all the papers in it. • A book where you keep all your notes and drawings during a design project. • I understood design journals as a place to keep a record of the design process. It is a way to keep your thoughts in once place so that you may review previous work at any time. • I believed design journals were a useful medium to collect and organize thoughts and ideas on a complicated design project.

Question nine shows the level of understanding what a design journal is and what it's used for was proficient for a senior level student. This question also reveals the note taking experiences of the students and also the fact that most of them have never used a design journal even though they have all had previous design experiences. This is not a negative result; it just shows the prior experiences of the students. It was unexpected that some students knew exactly what a design journal was and what should be included inside one. An interesting follow up question to this one could have been: *Where did your definition of a design journal come from?* That would reveal the source of the definition whether it was a previous design instructor, a parent, or other origin.

Topic 2: Thought process improvements because of the design journals. This question is important because it reveals if the students increased the amount of writing from what they had done in a previous design related course. The students at UMD have a junior level design course (ENME 371) where they work on teams on a re-design of a DeWalt hand tool product. The responses from Student Design Study 3 are given in Table 59.

Table 59: Student Design Study 3 Question 6 Responses

Q6: Did you write more than you have in previous design courses?
• *Yes (6)* • *No (3)* • I believe I wrote more pertaining to our project then I have in other courses. • I probably wrote about the same amount that I did in ENME 371. Maybe a little more since the homework's required more writing. • As mentioned earlier, a lot of the parts of the design process in other classes were implemented immediately or just thrown into outlines that would be thrown away eventually. The design journal caused me to write a significant amount more. • I definitely have written more in this design course than any other course. • I believe I wrote more pertaining to our project then I have in other courses. • About the same. Just now more in one place. • The notes that I took were the same that I would keep in any other class. • Keeping a design journal helped me write down more of my ideas than I normally would. As a result, it was very helpful to me to sort through all of my ideas.

Question six shows that the majority students in Student Design Study 3 increased their total writing time for a technical course. Thought process improvements are linked to written journals of any kind and in many situations beyond design. One student noted that the type of homework assignment was the cause for increased amount of writing for this course and not the use of the design journal. The design journal was a helpful place for another student to sort through their design ideas, which is an expected benefit.

Topic 3: Sketching during the design process. Sketching during the design process is known to improve understanding and certain spatial abilities. Question Five highlights the sketching activities of the students before and during the study. This question can reveal the student's history with sketching and if using the design journals changed their normal sketching routines. Sketching during the design process is essential for engineering designers and many other professional designers. Student's access to CAD and other programs sometimes deters them from hand sketching during the design process. The responses from Student Design Study 3 are given in Table 60.

Table 60: Student Design Study 3 Question 5 Responses

Q5: Do you normally sketch? Did you sketch more with the design journals?
• *Yes (6)* • *No (3)* • If the project needs sketches or to get ideas across I will sketch to help others understand a layout or idea, I think I sketched about the same with the design journal. • I sketch quite often to get concepts down. I would not say I sketched any more so with this journal. • Normally I would just make a rough CAD drawing to illustrate whatever concept I had in mind, since I'm fairly proficient and it's easy to show other people how the concept works. • I am not very artistic, so most of the time when a sketch is required; I opt to make something in CAD because it's generally easier for me and clearer for everyone else. The journal forced me to sketch my ideas way more than usual. • I did not normally sketch and the design journal did help me sketch ideas and work through ideas with my group. • If the project needs sketches or to get ideas across I will sketch to help others understand a layout or idea, I think I sketched about the same with the design journal. • I normally just make rough sketches in random places. With the journal I put them all in one place. • I sketch everything. The design journal provided a place to keep all of my sketches. • I do normally sketch out my ideas. I do not think I sketched more with the design journal but it was a convenient medium to use.

Sketching is revealed as a valuable tool for helping others to understand a layout of design ideas. The students reveal that they did sketch not more while using the journals and for the capstone course. It is surprising that the majority (6) of the students claim established sketching practices before participating in the design journal study. The students seem to like the idea that now they would have all their sketches in the same place. Two students did admit that they were not great sketchers and would prefer to make a rough design layout in CAD because that is where their proficiency lies.

Topic 4: Journal layout questions. This question is important for the future administration of design journals in the classroom. The Design Journal Guidelines (Figure 65) as shown in the appendix reveal slight changes from one Student Design Study to the next. The responses from Student Design Study 3 are given in Table 61.

Table 61: Student Design Study 3 Question 10 Responses

Q10: Were the instructions clear enough for this study?
• *Yes (8)* • Everything was explained to me very clearly. • It was a little unclear how we were supposed to write everything (whether it was supposed to be in coherent sentences or just bullet points) because we were given very little direction, but I found that the journal took on the formatting that I was the most comfortable with which was probably more advantageous than having a set format. • Could have used a sample journal to look through before starting. • The instructions were very concise. • The instructions were very easy to understand and follow.

Question Ten confirms that the instructions for the study were effectively constructed for 8 out of the 9 students. One student did not clearly state a yes or no just gave a suggestion that we could have made a sample journal available to look through at the beginning of the study.

Topic 5: Effectiveness of the design journals during the design process. This topic is important because the realization of the benefits of using the design journal is important for this research. The responses from Student Design Study 3 are given in Table 62.

Table 62: Student Design Study 3 Question 2 Responses

Q2: When did you fill out the journal?
• Anytime my team was meeting or if I was brainstorming on any ideas about the project. • During group work and brainstorming myself. • I filled out the journal during meetings and used it to create outlines for reports. Therefore, a majority of the writing in the journal normally took place just before a deadline. However, I also filled in ideas that were discussed during meetings and used it to further develop potential concepts. • Most of the items in my journal came from group meetings, though some of the entries came when I was working alone on a specific section or brainstorming. • I tried to remember to fill out the journal during every meeting or when I had thoughts of my own. • Anytime my team was meeting or if I was brainstorming on any ideas about the project. • During designing and research. • During team meetings, brainstorming, class, anytime I was thinking about the project. • I usually filled out my journal during team meetings and discussion sections when we were working on the project. I took notes whenever there was something important I wanted to remember to research or use later on.

Question two reveals that the journals were useful to most of the students during their team meetings. The design journal served as a place to record important design work that occurred during the team meetings. Other students also noted that they filled out the design journal when they worked alone on the design project or anytime that they had thoughts about the design project.

Topic 6: Improvements in the design process. The use of the design journal experience was new for the majority of the students; hence it is important to see if the journal increased the amount of time spent on the design project. The responses from Student Design Study 3 are given in Table 63.

Table 63: Student Design Study 3 Question 4 Responses

Q4: Do you think it added time to your design work?
• *Yes (1)* • *No (8)* • I think it sped up the process because all of our team project information was in one location. • They were things that needed to be written down anyway. If anything it kept my work contained to one location, which was helpful. • If anything it made me a more efficient engineer. • It definitely added time to my design work because the things that I'd typically scribble quickly or not write at all were being entered in a way that was easy for me to find it I needed to reference them in the future. • The design journal did not add any additional time to my design work. • I think it sped up the process because all of our team project information was in one location. • It was useful to look back and see what I wrote previously and see changes and improvements. • I write everything down multiple times anyway so keeping this journal was business as usual. • Adding notes to the design journal took time. But in comparison to the amount of time would have taken me to recall an idea I had, a reference I discovered, a design I wanted to follow or describe or anything I wrote in the journal, adding notes took very little time. In the end, I believe the design journal saved me time on my design work.

Question four shows that the students seem to have the time to write in a design journal. It also reveals some of the usefulness of the design journal such as seeing previous records, seeing changes and improvements, memory aids for previous ideas, easily locating references, and being a more efficient engineer. It seems that even in the case where a student felt that the design journal did add to the design time that it was worth it because the benefit of using the design journal outweighed the added time component. These responses are promising for future design journal studies in capstone design courses where student's time recourses are already limited.

Topic 7: Connections. This topic contains two questions, one and three. One of the benefits from using a design journal is the ability to re-read previously written notes when needed. This is also a benefit for analysis and calculations that will not have to be repeated if they are found previously in the design journal. The student's previous note taking routines are also questioned under this topic. The responses to question one and question three from Student Design Study 3 are given in Table 64 and Table 65.

Table 64: Student Design Study 3 Question 1 Responses

Q1: Did you ever make design notes during a previous design process?
• *Yes (6)* • *No (3)* • Would make notes in my notebook for that course. • Not in such an organized manner and in one place. • I made general design notes before, but they were never organized into a specific journal. They would have been dispersed throughout several notebooks and CAD programs. • I had never done anything quite like this. Most of my design notes were never actually written down. Instead, they were immediately implemented or lost in my notes from lectures. • I have never used a formal design journal. I had a small collection of papers that I kept together, but they were usually discarded after use. • Would make notes in my notebook for that course. • I keep a design journal of all my design processes. • They were not organized together. Generally, all my notes were taken on loose pieces of paper and were never compiled.

Question one reveals that students know how to take notes; this dissertation is assuming that such notes taken during design are important. The majority of the students took notes during previous courses but it seems like they did not always keep them in the same place or in an organized manner. The design journals served an organizational tool for some of the students. The student's journals included pasted in CAD drawings and other types of foreign inserts related to the design project.

Table 65: Student Design Study 3 Question 3 Responses

Q3: How often did you go back and read what you wrote? Did you add more notes or notations when you went back?
• Each team meeting I would look over what we had written the previous time. Generally this was a couple times a week. • Probably about once a week to refer to concepts that I came up with or calculations I had done to aid in the design process.

- I often found myself going back and re-reading what I wrote. I rarely went back and changed anything I had done before in order to show what I was thinking at the time of writing. I would often re-write old ideas in order to revise any old concept I had.
- I usually went back and re-read something about once a week because I'd forgotten it or someone else in the group asked a question that I already had written down the answer to previously. I rarely went back to add more notes to pre-existing sections.
- I only went back to read what I wrote when it came to writing reports. At that point I just added what I needed to my writing. (Referring to the report)
- Each team meeting I would look over what we had written the previous time. Generally this was a couple times a week.
- I usually checked back on the notes when I needed information or past calculations. I corrected past mistakes if present.
- I would review the previous week's notes at the start of every week.
- I normally would go back and read my notes over every time I worked on the project. My notes consisted of many of the ideas and problems associated with the project. Every time I needed to refer to one of these ideas or problems, I would go to my design journal. If I had a new idea to add or an idea I wanted to update, I would go back and modify my notes.

Question three reveals that the students did re-read the notes that they wrote in their design journals. The students stated that they went back during team meetings, once per week, and when they needed to refer to past calculations. This is something that actually saves them time during their design process whether they realize it or not. The majority of the students did not often change what they wrote, but may have just added additional notations where needed to update the information in the design journals. Just two students note that they modified previous notes made during the design process, one in the form of making corrects to past mistakes. Correcting a mistake made during the design process can be crucial to the final design and ultimately cost a company time and money if overlooked by the engineering designer.

Topic 8: Recommendations. This question is seeking the student's input on the possible implementation of design journals in the capstone design course in future sections at UMD. The responses from Student Design Study 3 are given in Table 66.

Table 66: Student Design Study 3 Question 8 Responses

Q8: Do you think design journals should be a course requirement in design courses?
• *Yes (4)* • *No (4)* • *Optional (1)* • I think it would greatly help for students to keep all their information in one journal instead of possibly having papers all over the place. • I think they should be encouraged but voluntary. • I think it would be a good idea to suggest and provide the necessary materials for a design journal. But I don't think people who don't want to participate should be forced to. • I do not think design journals should be a requirement because they are a type of learning that is only helpful for certain types of people that like writing down everything they do as a way to keep themselves organized. • I think that making them a requirement might defeat the purpose of using them. Student should be provided one as a resource or guide. • I think it would greatly help for students to keep all their information in one journal instead of possibly having papers all over the place. • I should be optional for design courses. If required it should not be graded because that limits personalization. • I do not think so. Everybody has their own design process and students should not be forced to keep a journal if it does not benefit their productivity. • I think students could greatly benefit from using a design journal to keep track of their ideas and through processes.

For the purposes of the Capstone Design Course Question Eight shows that the students are divided as to whether the design journals should be a requirement for the course.

Topic 9: Positive Impacts. The impact that participation in this study had on the students is important because it reveals potential changes in behavior that result from the students design journaling experience. The responses from Student Design Study 3 are given in Table 67.

Table 67: Student Design Study 3 Question 11 Responses

Q11: Will you write design notes again during a future design process?
• *Yes (8)* • *No (1)*

• Potentially, if I do further design. I am not sure whether I will be or not in the future. • It is very likely that I will keep some kind of notes during my next design project. It may differ slightly from the current format but I doubt it will be very different. • I am more comfortable not using a design journal because I found myself unenthusiastic about using the journal when I really started getting into doing design work. It sometimes felt like it was taking energy away from the design effort and shifting focus away from what I wanted to be working on. • I will continue to write notes, whether or not they will be all in one place is another story. • Most likely yes. • I absolutely will. I habitually take notes and sketches on almost everything that I do. • As a result of this experience I feel that I will use a design journal much more often on future projects.

Question Eleven proves that almost all of the students would use design journals again in the future or some type of note taking process. One student notes that they are not comfortable using the design journal and that they lack the enthusiasm to produce one in future design projects. This design study had a positive effect on the note taking habits of some students who participated.

Topic 10: Negative Impacts. Understanding that not all the students will reap the benefits from using the design journals because they don't use them properly, it is important to highlight the negative reactions from the participants. The responses from Student Design Study 3 are given in Table 68.

Table 68: Student Design Study 3 Question 7 Responses

Q7: Did it feel awkward to use the design journal?
• *Yes (5)* • *No (4)* • It helped keep me organized with where all the information was kept. • At first, but once I figured out how I wanted to use the journal it was not as difficult. • Especially in the beginning of the semester when I was constantly having to remind myself to go into the journal and write down everything important that was happening. • I believe it only felt awkward to use the journal because it was such a formal way to take notes. • It helped keep me organized with where all the information was kept.

- It was awkward because I'm used to making sketches and calculations on whatever is available and showing other people easily without having to give my whole notebook.
- I personally did not like the paper of the journal or the binding so it was a bit annoying. Pencil did not show up very well and I like to write on hard surfaces so a notebook that could not be folded over was a bit difficult.
- At some points it felt strange trying to convey what was in my head onto paper. But, I know this ability is a necessity in engineering work. Therefore, I am glad the journal helped me overcome the awkwardness of writing down my ideas.

Question seven highlights the fact that these students were not initially comfortable using the design journals, although some of this early awkwardness eventually wore off. One student felt that using the design journal was a very formal style of note taking. Organization is something that 2 students noted as a benefit that outweighed the awkward feeling or using the design journal.

Overall, Student Design Study 3 participants would agree that the benefits of keeping a design journal outweigh the preconceived hassle. It was surprising that some students used their journals as only a collection folder for other documents created using a computer. The benefit to having a designated place for notes for the course was a common theme from the students which helped their organization.

5.7 Conclusions

5.7.1 Quantitative Conclusions

This rich data set from coding of the design journals allows for a variety of analysis that could be performed. The quantitative conclusions from this chapter are:

- Table 35 (Page 117) shows that there are differences in journaling behavior by design phase of students in Student Design Study 1. This means that student in the same course with the same journaling instructions will not necessarily journal the same throughout the entire design process.

- Table 36 (Page 119) shows that there are differences in journaling behavior by design phase of students in Student Design Study 1 and Student Design Study 3. This reveals the differences in class structure and motivation behind journaling behavior.
- Section 5.1.6 shows that there are significant differences in the activity densities between the three student studies. This is most likely because of the administration changes made in each study.
- Table 41(Page 125) through shows that most of the students have a good representation of a variety of cognitive codes used in their design journals. (With the exception of Journal 1 and Journal 3)
- Table 50 (Page 132) shows the results from the stated hypothesis. This could be explained by the size of the data set, maybe a larger study would yield different results.
- Table 52 (Page 135) and Table 53 (Page 136) show the concept developments for Student Design Study 1 (Team Study) and Dr. Sobek's team. These tables highlight the fact that the same and even higher level of participation is shown for the students in Student Design Study 1 versus Team S from Dr. Sobek.
- Section 5.5 concludes that the use of the Smartpen technology does not have an effect on the journaling behavior of students across 2 teams.

5.7.2 Qualitative Conclusions

Understanding the journaling experiences of students is important for this dissertation and future studies wanting to implement design journals in the capstone design course. The qualitative conclusions from this chapter are:

- Student's attitudes towards the use of a design journal are quite favorable and they seem to have realized the benefits over the use of the design journals for the entire semester.
- Implementing new tools to aide in the design process such as design journals might feel awkward at the beginning but the benefits seem to overcome this for the students in this study. Unchartered territory can seem strange until its usefulness is revealed over time.

Chapter 6: Professional Design Study 1 Results

This chapter presents a number of results and discussion from the Professional Design Study 1. Professional Design Study 1 included the project of the professional engineer recorded in three design journals over a period of five years that have been coded for this dissertation. The professional engineer mentioned in this dissertation is Mr. Leland Engel who, at the time of writing the design journals, was a research engineer working for NASA stationed at The Pennsylvania State University. Mr. Engel has a B.S. in Mechanical Engineering from The Pennsylvania State University and a M.S. in Engineering Management from University of South Florida. He has over 30 years of experience as a mechanical engineer.

The project that Mr. Engle was working on at the time he was recording in the design journals was a satellite that launches from a Pegasus XL rocket in 1996. As the research engineer he was responsible for everything mechanical on the satellite. This included electronic boxes (both analog and digital), camera design, thermal, heat transfer, vibrations, and shock work. At the time he was the only mechanical engineer on the team. Although based in State College, PA he spent time in Argentina, Brazil, Washington, DC, and Wallops Island, VA working with other scientists and team members on this particular project.

The journals of a professional designer are important because it gives this dissertation the start it needs for observing professional design behavior. The students in the previous chapter are striving to become professional designers and comparing between what they are doing with the professional's journaling activity is important for this work.

The students were given guidelines as to how they were to create their design journals; the professional designer had no such guidelines. However he created an abundant design record that proved to be extremely useful for this design research. Section 6.1 looks inside the professional's design journal records enumerating design sessions, design segments, activity density, and design phase results. The second section (Section 6.2) presents the types of cognitive activities that were found in the professionals design journal. Then (Section 6.3) presents the concepts that were traceable in the professional's design records. Section 6.4 looks at the visual representations used by the professional in the design records. Finally, (Section 6.5) details perspectives on using a design journal from the professional engineer.

6.1 Inside the Design Journals

The professional design journals were coded in order to reveal cognitive activities cues. The three design journals were dated from 1991 to 1996 and were almost all completely filled in. Design journal #1 had 80 pages, front and back. Design journal #2 had 300 pages. Design journal #3 had 46 pages, front and back. The total number of design journal pages for the entire project is 563 spanning a 5 year time period.

The professional design journal was found to have 891 total design sessions and 2278 design segments. The activity density for the professional engineers design journal segments and sessions is 2.55. Similar to the student's journals, loose leaf papers were found stapled and glued into the professionals design journal. The vast majority of the entries in the design journal were found to be dated and 55 entries contained the signature of the engineer. Table 69 shows the details by journal for the design sessions, design segments and activity density.

Table 69: Professional Design Study 1 Results

	Design Sessions	*Design Segments*	*Activity Density*
Design Journal 1	208	732	3.51
Design Journal 2	566	1210	2.13
Design Journal 3	117	336	2.87
Average	297	759	2.83
Standard Deviation	298.7	437.6	0.69

Table 70 shows the percent of each design phase found by design journal. Keep in mind that this project was over several years the majority of his time was spent doing detailed design. The small amount of time spent during conceptual design is surprising but it may be that the problem statement was well structured and also that the limitations of the constraints meant he didn't need to explore this phase that long. Also the embodiment design phase was done for only less than half of the first design journal, this could possibly be explained by his expertise in the field.

Table 70: Professional Design Study 1 Design Phases per Journal

Professional Design Study 1 Relative Activity per Design Phase				
Journal	*Conceptual Design*	*Embodiment*	*Detail Design*	*Redesign*
1	6%	0%	94%	1%
2	0%	0%	100%	0%
3	0%	0%	100%	0%

<u>*6.2 Cognitive Activities*</u>

6.2.1 Cognitive Codes

The 35 cognitive codes were applied to the three design journals in order to further understand designer thinking. The codes are shown in Table 11 in Chapter 3. The expectation was that more design details and types of cognitive activities would be found than were seen in student journals. The results are shown as percent of total design segments in Figure 31 organized by cognitive class. The results from the cognitive coding scheme for the professional will be discussed by percent of segments in each cognitive class in the next sections.

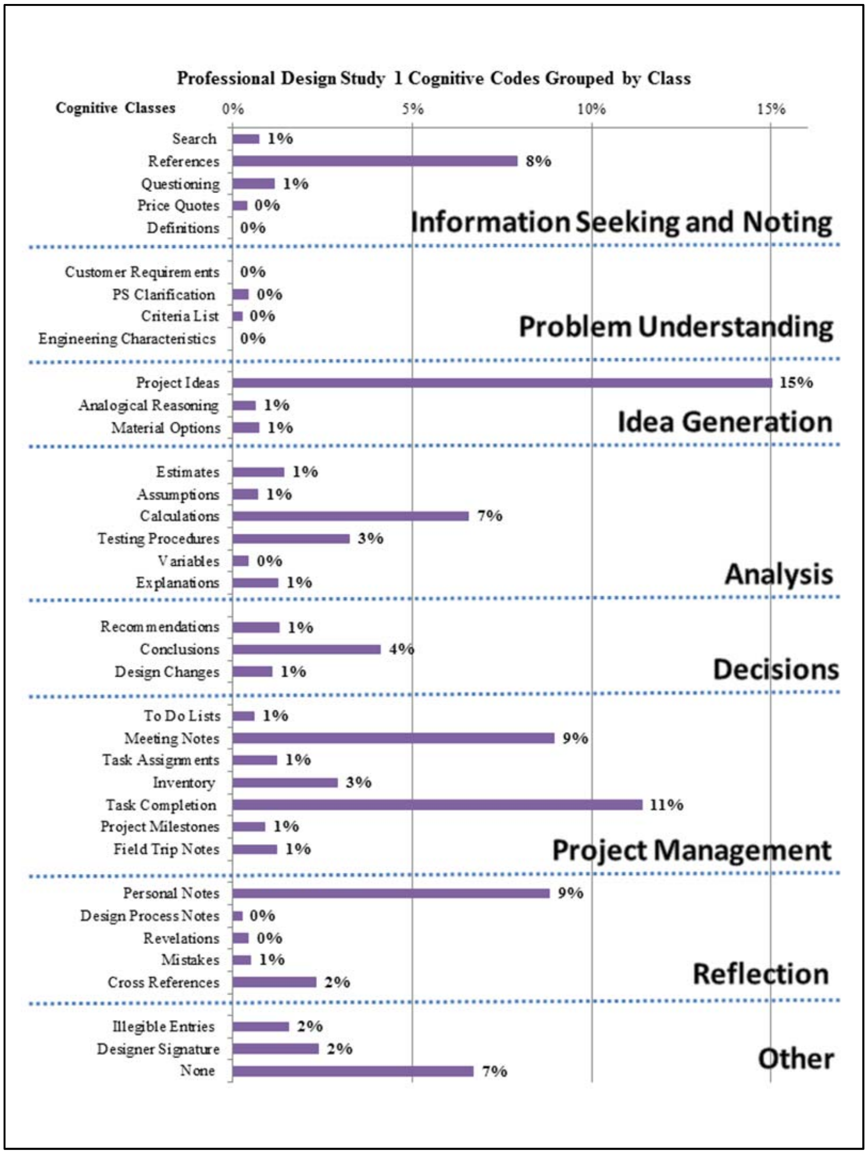


Figure 31: Professional Design Study 1 Cognitive Code Results by Class

The results from the cognitive coding scheme for the professional are shown by month in Figure 32. This figure highlights cognitive activities found over the entire time that the professional was recording the design journal.

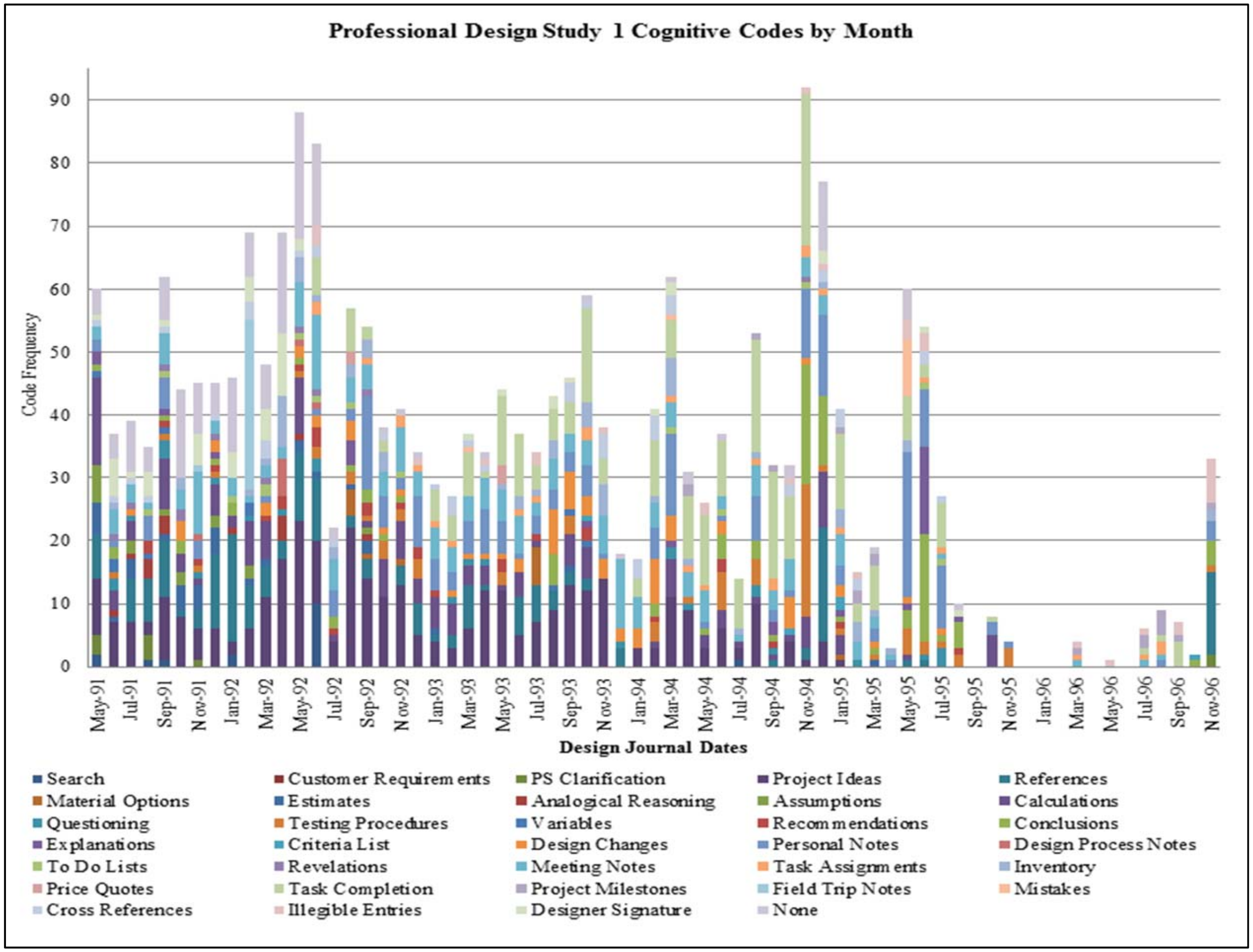


Figure 32: Professional Design Study 1 Cognitive Activities over Time

The spider plot shown in Figure 33 shows that the majority of the cognitive code class in the professional's design journal was project management. The project management class includes things like meeting notes and task assignments. This reiterates the importance of project management tasks that are needed to complete a design project. This project was global and involved several contractors and other businesses working together to achieve this design goal. In order for the project to be successful each member of the team had to take responsibility for their specific part of the design project. The classes shown in this figure are discussed in detail in the next sections, with one section dedicated to each class.

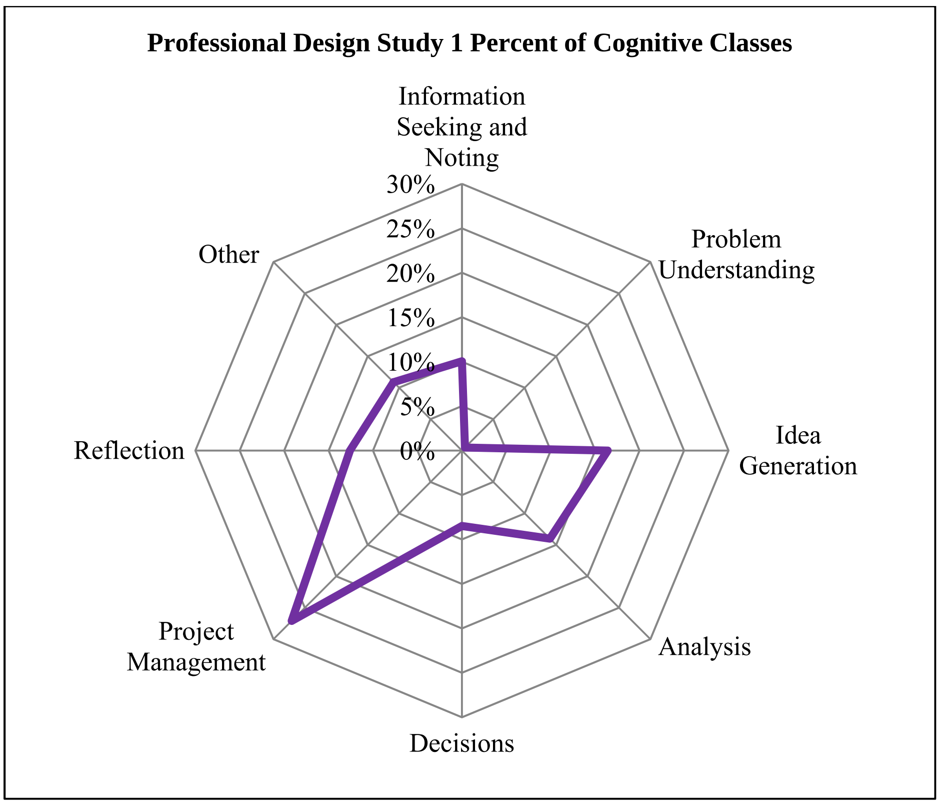


Figure 33: Professional Design Study 1 Cognitive Classes by Percent of Design Segments

6.2.2 Information Seeking and Noting Class

Information Seeking and Noting class results are shown as percent of total design segments in Table 71 and by month in Figure 34. *References* are the highest code in this class. A note stating where information came from was expected because the professional would certainly need to re-visit the information to aid in future decision making. Any engineer who spends lots of time searching for information regarding their project would want to document where they found the information so that they can reference it at a later date. If a book or technical publication was read, notes about this would probably be in the design journal in relation to the project at hand. Leland relied heavily on reference books with constants and formulas in them to work out his calculations. Since he was designing several components at one time he also needed to rely on outside expertise, which was found in the design journals. He used the journals to write who said what and when they said it especially when what they said had an influence on the design. It was certainly noted when he got information from someone else.

Table 71: Professional Design Study 1 Information Seeking and Noting Cognitive Class Results

Cognitive Code	***Cognitive Cue***
1. Information Seeking and Noting	
1. Search	0.75%
5. References	7.95%
11. Questioning	1.19%
26. Price Quotes	0.40%
36. Definitions	0%

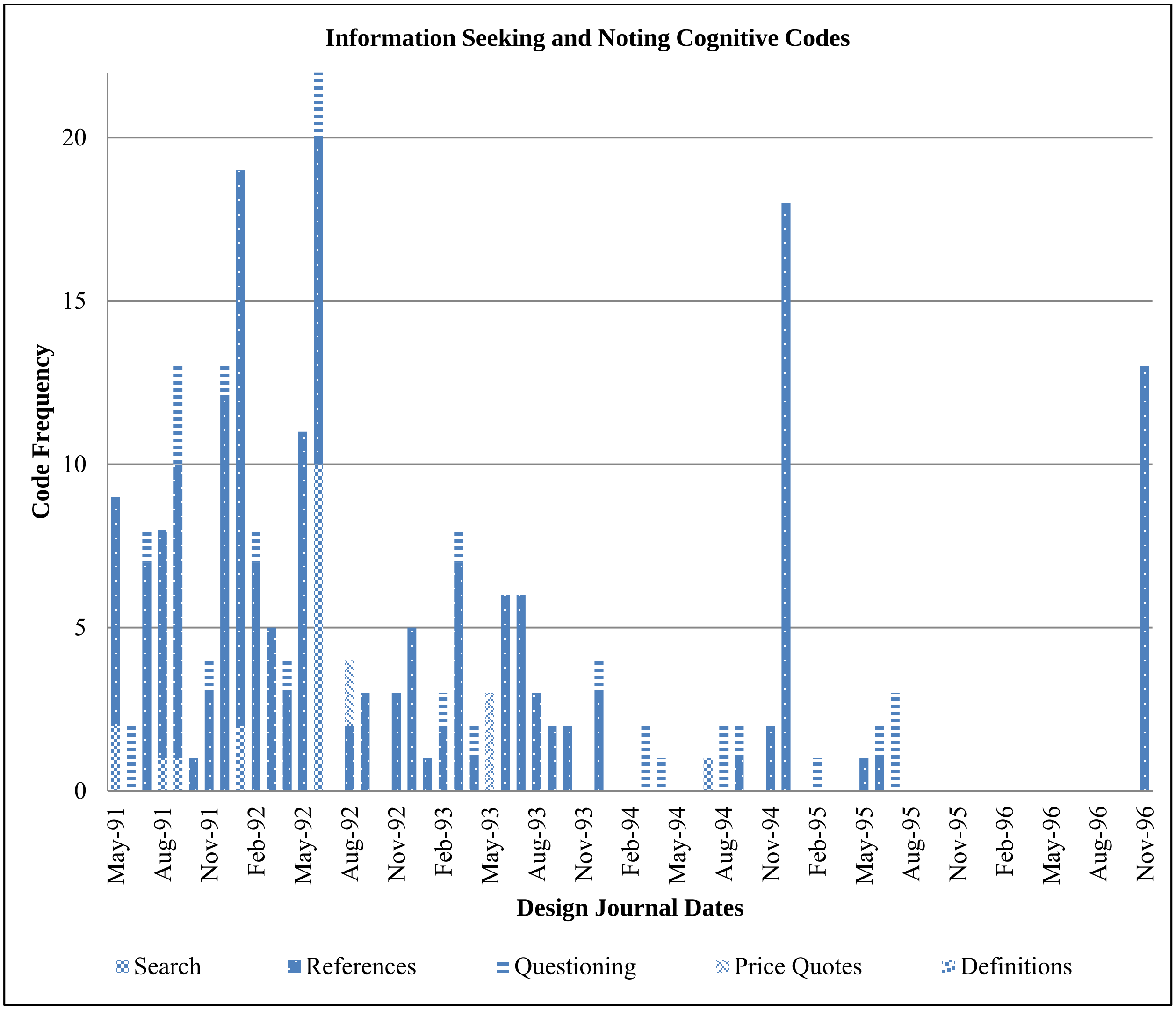


Figure 34: Professional Design Study 1 Information Seeking and Noting Class Codes by Month

It is clear that the information seeking and noting codes were mostly used at the beginning of the design process. The code for *References* was used the most probably when gathering information for the project needed to make important design decisions. The types of references found in the journal were pasted in charts and tables, information about specifications, catalog pages, and information copied down from a book. This type of information was displayed as very critical to the design project at the beginning stages. It should also be noted that the 3 design journals ended in June 1992, November 1994, and November 1996. In Figure 34 these dates seem like outliers because they are different. At the end of each of his design journals he included many reference materials that seem to have been those go-to items that he needed to reference most without having to flip through the journal. The references found on the last few pages and even the inside of the back cover of the journal probably were placed there prior to the dates shown.

Questioning was seen in the form of lists to ask other people and also the talk about during team meetings. Also e-mails to and from Leland with questions related to the design project was pasted into the design journal. The cognitive code *Definitions* were not found in the professionals design journal, this code was added after the professional's design journals were coded because it was something that was found in Student Design Study 2 journals. Only a few *Price Quotes* were found in the professional's design journal.

6.2.3 Problem Understanding Class

The Problem Understanding class results are shown as percent of total design segments in Table 72 and by month in Figure 35. The code *Customer Requirements* actually did not occur at all which could mean that he put it in a different way. This would mean that the coder might not have picked up on who was the customer and when he was dealing with them through the journal records. The cognitive codes *Criteria List* is found in less than one half percent of the cognitive codes.

Table 72: Professional Design Study 1 Problem Understanding Cognitive Class Results

Cognitive Code	*Cognitive Cue*
2. Problem Understanding	
2. Customer Requirements	0%
3. Problem Statement Clarification	0.44%
17. Criteria Lists	0.26%
37. Engineering Characteristics	0%

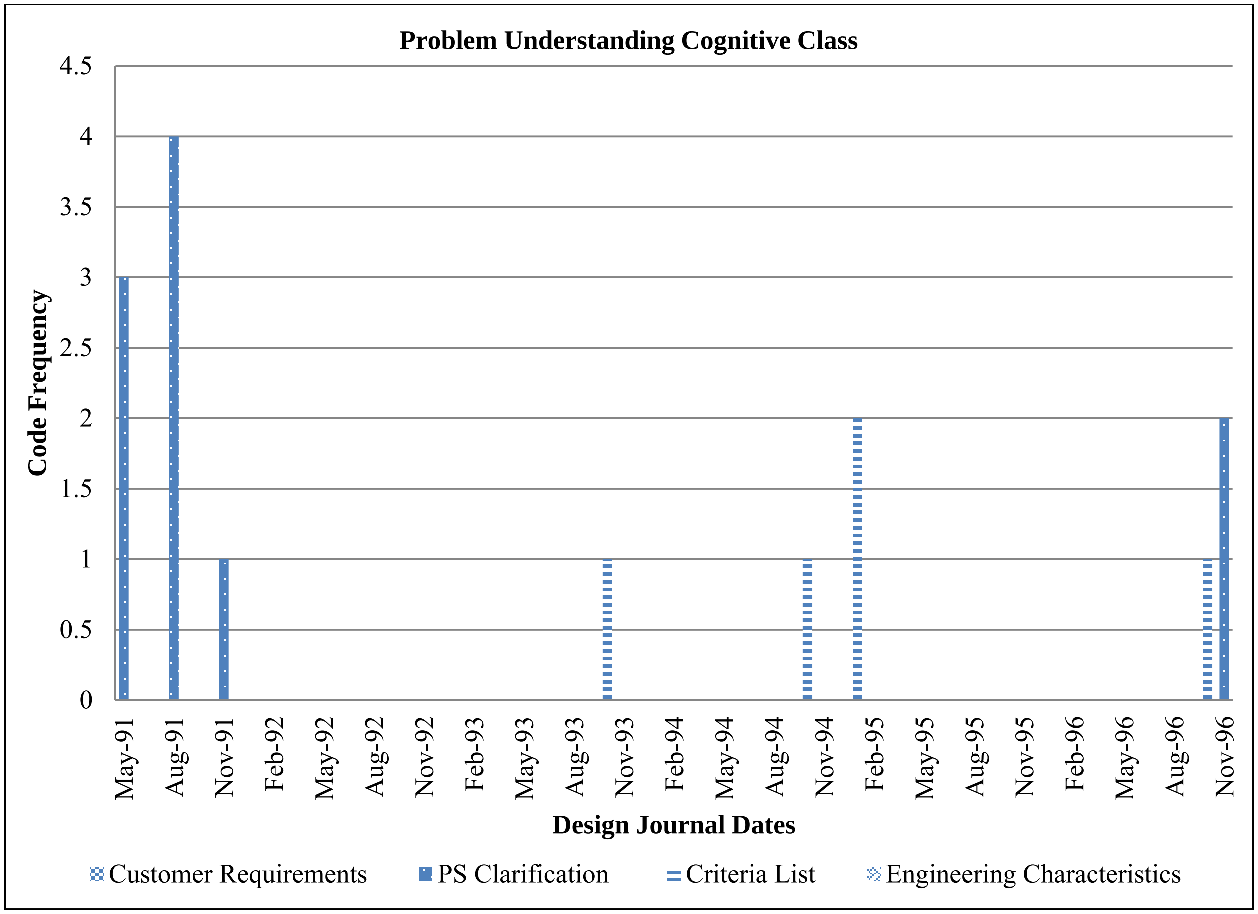


Figure 35: Professional Design Study 1 Problem Understanding Class Codes by Month

Problem understanding codes did not come up frequently in the professional's design journal. This was a surprising result, but it could mean that the problem that he needed to solve he was already familiar with because of his previous experiences in this field. As a professional engineer his employer would probably not give him the responsibility for a project that he was not at least somewhat familiar with and capable of coming up with the best solution. At the very end of the design journal he pasted in to sheets of project goals which were coded as *Problem Statement Clarification* because it was a document that discussed what the goals of the project were. These sheets did not reference where the project was so they could also been seen as a reference document. The were no codes for *Engineering Characteristics* because this was also a code that was added after the professional design journals were coded from information found in Student Design Study 2 journals. There were also no codes for *Customer Requirements* which could be a testament to the fact that either he had no contact/interest in the customer or that he had sufficient knowledge already enough to understand their needs.

6.2.4 Idea Generation Class

Idea Generation class results are shown as percent of total design segments in Table 73 and by month in Figure 36. The *Project Ideas* cognitive code is found the most in the journal, accounting for 15% of the total cognitive codes. This is not surprising because a design journal is the best place to records new ideas about the project. It was expected that the professional would be expected to come up with lots of solutions and ideas to solve the design problem.

Table 73: Professional Design Study 1 Idea Generation Cognitive Class Results

Cognitive Code	*Cognitive Cue*
3. Idea Generation	
4. Project Ideas	15.01%
8. Analogical Reasoning	0.66%
6. Material Options	0.75%

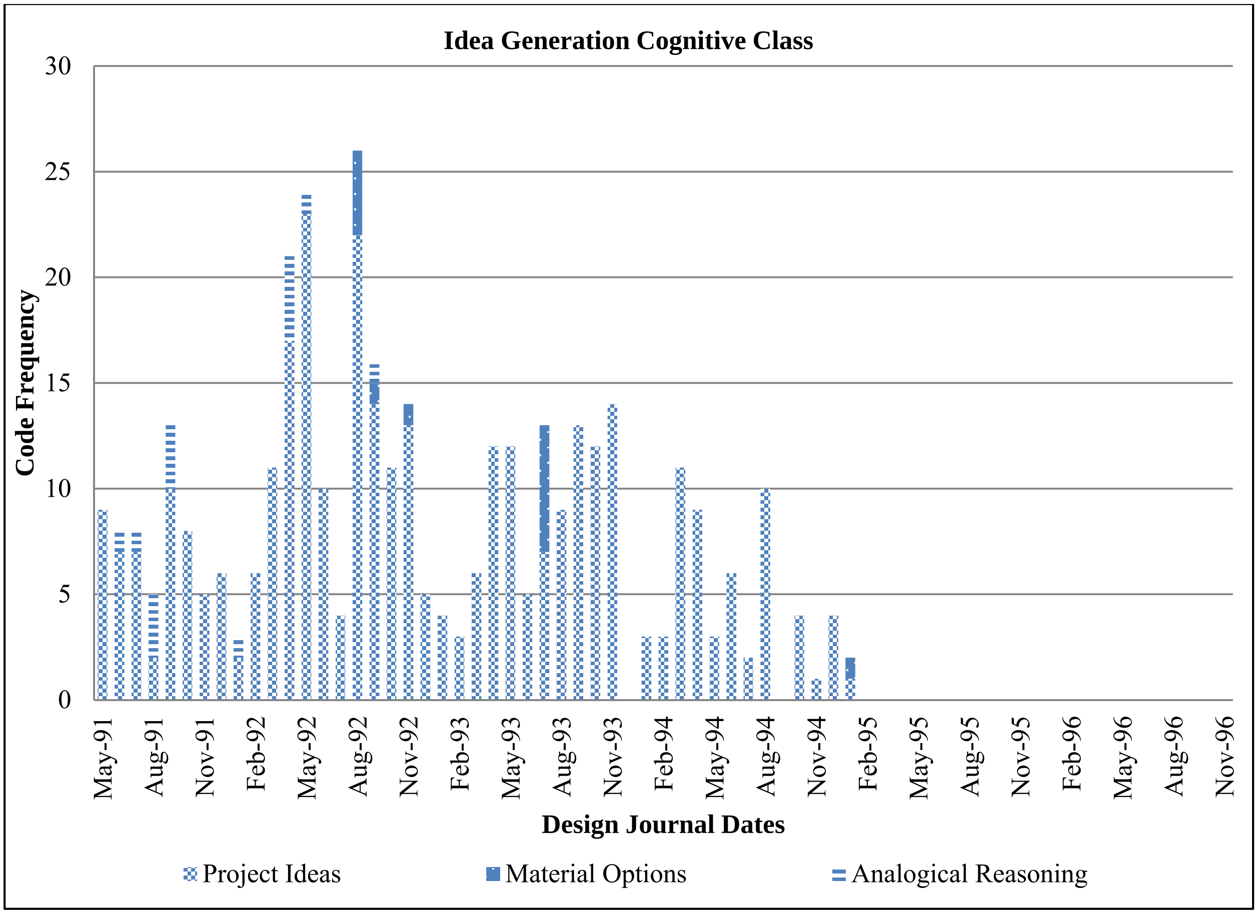


Figure 36: Professional Design Study 1 Idea Generation Class Codes by Month

The majority of the idea generation codes were for *Project Ideas* and very few were *Material Options* and *Analogical Reasoning. Project Idea* codes included sketches of different options for components, CAD drawings (one view, three views, and exploded views), Electrical Diagrams, and written list of design options. The sketches are interesting because they were detailed and varied in size from full pages to tiny corner drawings. Most of the sketches were annotated with text and some were even done in different color pencils to distinguish between component parts. *Material Options* were found as handwritten notes about different materials and their properties. The cognitive code *Analogical Reasoning* did not come up that much in the professionals design journal and this could mean that this code just does not apply for this particular professional.

6.2.5 Analysis Class

Analysis class results are shown as percent of total design segments in Table 74 and by month in Figure 37. *Estimates* found in the professionals design journal were mostly related to mass budgets. Space travel has weight limitations and certain criteria that have to be met so every so often the professional engineer would go back to the mass budget to review the weights of the components that he was designing. Each time the budget appeared it would show the weight of each component including notes about what they meant for the design project. *Calculations* are the 7th highest of all the cognitive codes. Calculations were expected to be the leading entries in the professional engineers design journal. Calculations are critical to design problems, and so are recording them for key design decisions and future reference. Key project calculations at times decide what materials to select, dimensions for parts and supplies, acceptable tolerances to name a few. The validation of the calculations for design is crucial because the negative consequences can be severe. If a design fails the blame could partially lie with the design engineer. His work seems very credible and dependable because he made checking of calculations he made they would be used without being questioned or scrutinized because he already took the time to scrutinize them. He also did things a few different ways and then decided which method was best and which method gave the most accurate answer. He included numerous sketches with his calculations and in other places. Charts and Results were found regarding different testing experiments that were run. These were coded as *Testing Procedures.*

Table 74: Professional Design Study 1 Analysis Cognitive Class Results

Cognitive Code	***Cognitive Cue***
4. Analysis	
7. Estimates	1.45%
9. Assumptions	0.70%
10. Calculations	6.58%
12. Testing Procedures	3.25%
13. Variables	0.44%
16. Explanations	1.27%

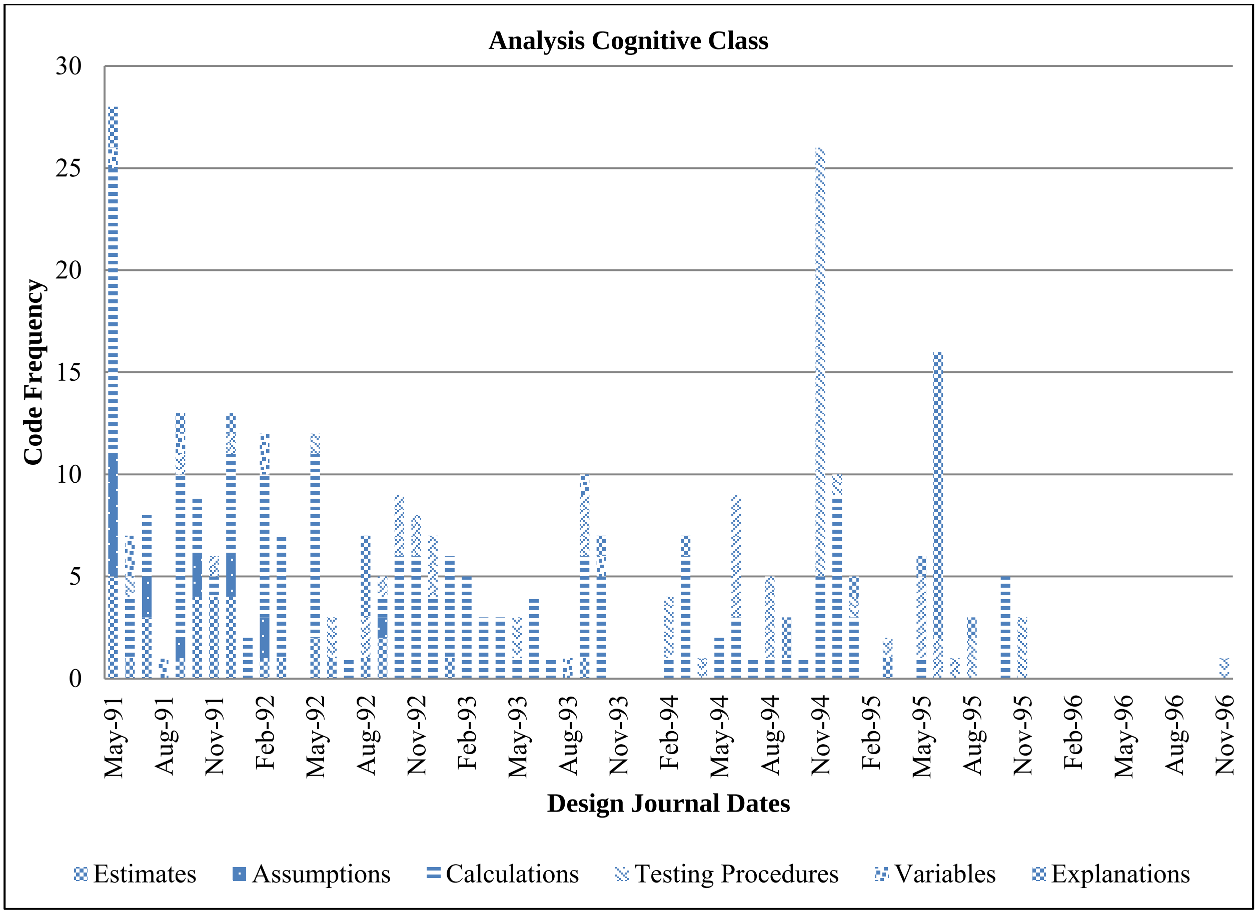


Figure 37: Professional Design Study 1 Analysis Class Codes by Month

The analysis codes show up at a consistent rate in the beginning and middle stages of the design process. Towards the end of the design process these codes don't seem to have any importance to the professional anymore. *Calculations* are the most consistent of all the analysis codes and this is in line with what is expected at the professional design level.

6.2.6 Decisions Class

Decisions class results are shown as percent of total design segments in Table 75 and by month in Figure 38.

Table 75: Professional Design Study 1 Decisions Cognitive Class Results

Cognitive Code	***Cognitive Cue***
5. Decisions	
14. Recommendations	1.32%
15. Conclusions	4.13%
18. Design Changes	3.07%

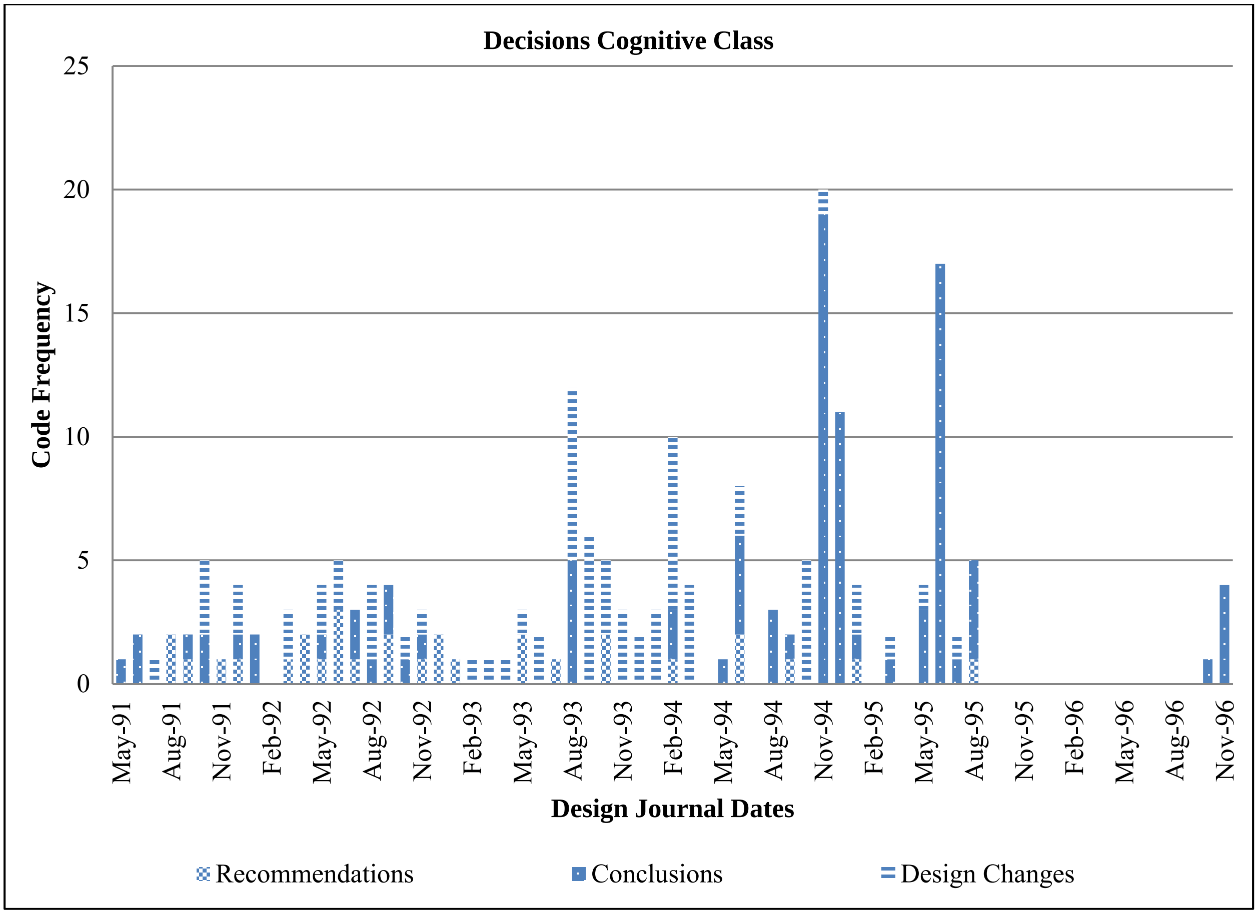


Figure 38: Professional Design Study 1 Decisions Class Codes by Month

Decisions are very important for any design project. The decision cognitive class experienced a spike towards the end of the middle of the design project. The types of *Recommendations* found in the professionals design journal were notes saying “Talked with Tony about X, he recommends Y” or “Tina at ABC Company says she recommends Z”. The types of cues to *Design Changes* found in the professionals design journal were “Modifications”, “I changed X”, and CAD drawings found with hand written notes about changes that were made. *Conclusions* that were found in the professionals design journal were testing results in the form of charts and tables and important decisions from management. Testing results were recorded at different stages of testing. When the test failed, it was noted and further entries involved trying to figure out what went wrong. He was very specific for example one time he notes that “1st staged burned at X minutes”, ‘2nd stage burned at X minutes”, and “3rd stages burned at X minutes”.

6.2.7 Project Management Class

Project Management class results are shown as percent of total design segments in Table 76 and by month in Figure 39. The 2nd and 3rd highest overall cognitive codes are *Task Completion* and *Meeting Notes* with 11.41% and 8.96% respectively. Meeting notes were expected because of the large scale and interdisciplinary nature of many professional engineering projects. An engineer participates in team meetings on a regular basis, probably weekly. In a meeting where the project manager is handing out tasks to the design engineer will probably be recorded. Faxes and E-mails with meeting notes and agendas were found in the professionals design journal. The professional would make “PSU Action Item Lists” and “Action Items from Tony Lists” and these were coded as *Task Assignments.* Another *Task Assignment* entry type found was notes about a part of presentation that he was responsible for. *Inventory* was important for the professional engineer because he was probably given a budget and responsible for staying within certain means. Types of *Inventory* records found were “Received X software and installed on the Y computer” and “Today Tony ordered X for me”.

Task Completion is the highest category for all cognitive codes in the project management class. It was somewhat surprising that he wrote down when he called people yet from a time management point of view he probably didn’t want to make repeat phone calls. Whenever the professional engineer would work on something, call someone, order something, schedule something, e-mail someone, fax a request to someone, ship something, or finish something he would make a note of it in his design journal. The e-mails were often printed out and pasted in the design journal for his records. Also, when he wrote that he called someone or that he had a meeting with someone he would record what the conversation was about. In the event that he called and did not talk to the person he was trying to reach he would note that he left a voicemail. When he was running experiments he would make notes about what he was going to run and why and after that he has completed X experiment.

There were not many *Project Milestones* coded but that does not mean that they are not important. One of the few was information about the official launch date for the satellite which is very monumental for this scale of a project. At some point in the design process he travelled to MIT to have a meeting related to this project. He notes many details about this trip including housing plans and travel itinerary; these were coded as *Field Trip Notes.* These codes speak to the fact that the professional was using his journal for project management. The importance of project management records is very important to him.

Table 76: Professional Design Study 1 Project Management Cognitive Class Results

Cognitive Code	***Cognitive Cue***
6. Project Management	
21.To Do Lists	0.61%
23. Meeting Notes	8.96%
24. Task Assignment	1.23%
25. Inventory	2.94%
27. Task Completion	11.41%
28. Project Milestones	0.92%
29. Field Trip Notes	1.23%

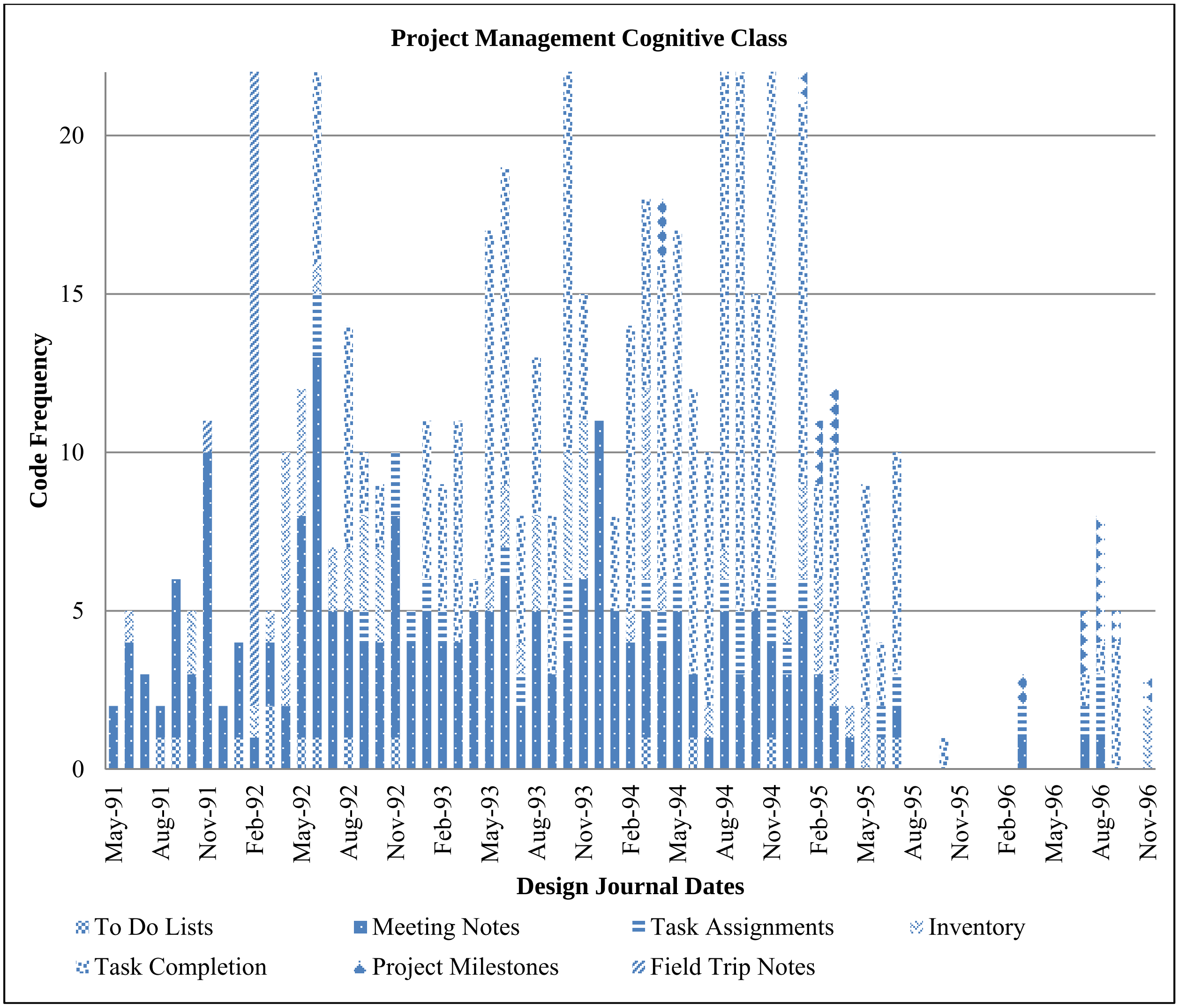


Figure 39: Professional Design Study 1 Project Management Class Codes by Month

Project management was very important to the professional designer and he was very consistent over time recording how he manages this project. It is clear that he attended a lot of meeting over the course of this project. These meetings may not have all been completely related to this project but they all had some kind of connection with the design project at hand. This shows that he was carrying his design journal with him when he was travelling to these meetings. He was working on a global team and therefore was travelling to different sites meeting with different people that were on this project with him. *Project Milestones* were not found that much in the professionals design journal but the fact that they were found is important because it means that he took time to step back and look at the big picture to see how this project was progressing. *Task Completion* was a code that was also found to be very consistent over the course of the design project; he was very particular about noting when he completed something. Any task that he did large or small he made a note about it in the design journal.

6.2.8 Reflection Class

Reflection class results are shown as percent of total design segments in Table 77 and by month in Figure 40. The cognitive codes *Design Process Notes* is found one of the least at less than ½ % of the cognitive codes. *Cross References* was an unexpected code because it was not seen previously in the students' design journals. It was unexpected to see that he went back and changed (or corrected) something in the design journal even after a year or two had passed to ensure the integrity of his calculations and notes throughout the journals. This makes sense for repeatability of his project utilizing his design journal. The design journal is also used for future projects as reference material and it was important to the professional that the records be accurate as possible. *Revelations* were not found that much in the professionals design journal. One example of a *Revelation* found is "Discovered X & Z are made of Y".

Some of the *Mistakes* coded were made very obvious by the professional by putting large red X's on them and also by writing the words "This is wrong". *Mistakes* were usually followed by a *Cross Reference* but not always. The fact that they are usually followed in that manner speaks to the integrity to which the professional wanted to keep his design records. *Cross References* was seen as "Previous Change made on MM/DD/YYYY", "See page XX for more information", and "Note: not good, see page XX". The fact that he included dates even when just cross referencing shows his meticulous attention to detail.

Table 77: Professional Design Study 1 Reflection Cognitive Class Results

Cognitive Code	***Cognitive Cue***
7. Reflection	
19. Personal Notes	8.82%
20. Design Process Notes	0.26%
22.Revelations	0.44%
30. Mistakes	0.53%
31. Cross References	2.33%

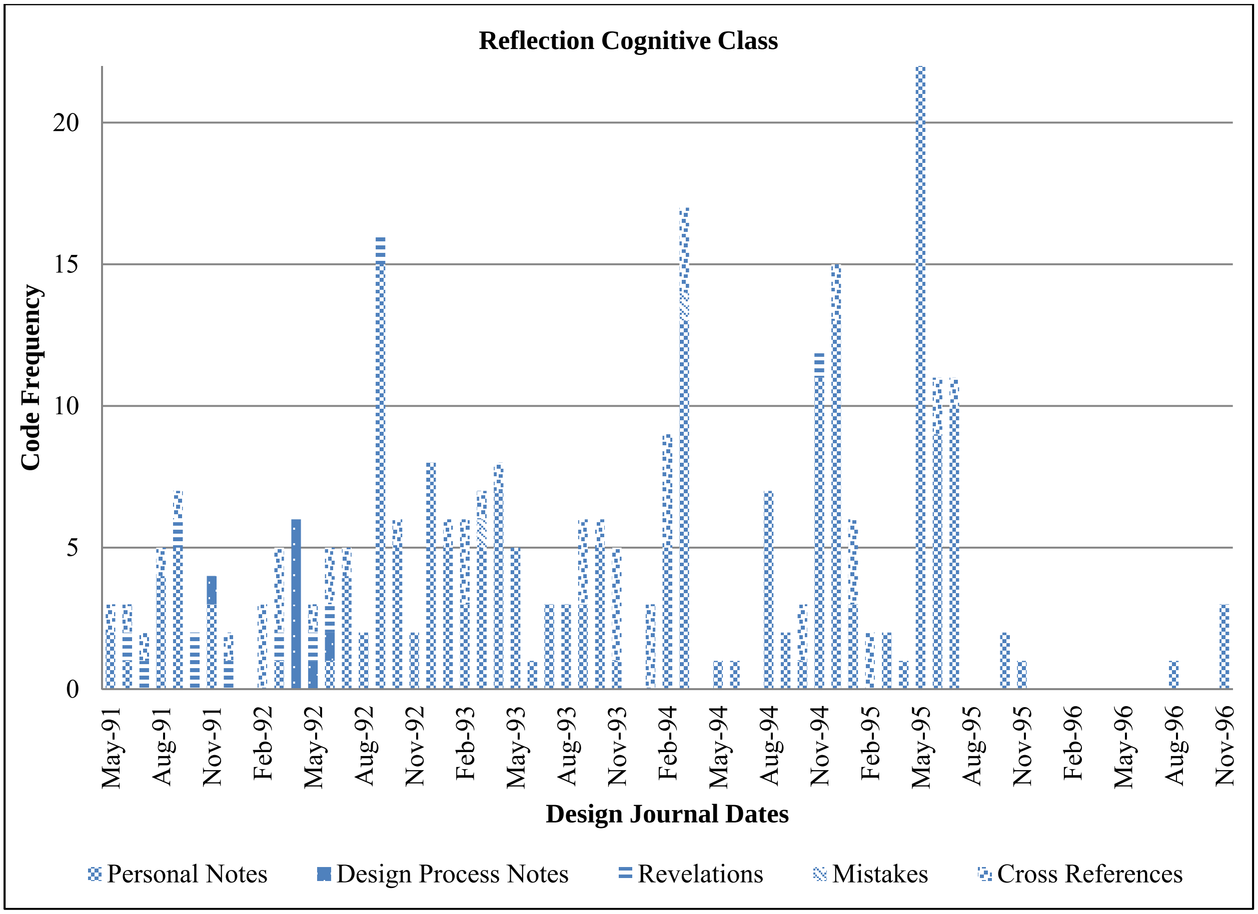


Figure 40: Professional Design Study 1 Reflection Class Codes by Month

6.2.9 Other Class

Other class results are shown as percent of total design segments in Table 78. Some of the entries found in the professionals design journal were just not readable, there were coded as *Illegible Entries.* As a professional engineer it may have been important for him to protect the propriety of the designs that he was coming up with. This meant that he should include his signature where original work was presented. *Designer Signature* was coded for things like sketches and CAD drawings. Records that were coded as *No Evidence of Cognitive Activity* were things like “Going on vacation”, Accounting numbers information, notes about where a building was on campus, and hotel information. He even noted when he was on travel and whom he was going to see while on travel. He even once noted that he gave money back to Tina (not real name) in accounting because he didn’t spend it all on his trip and it was a really small amount like $11 and most people would just pocket it.

Table 78: Professional Design Study 1 Other Cognitive Class Results

Cognitive Code	***Cognitive Cue***
8. Other	
33. Illegible Entries	1.58%
34. Designer Signature	2.41%
35. No Evidence of Cognitive Activity	6.72%

6.2.10 Cognitive Activities by Design Phase

During each part of the design process different types of cognitive activities can be seen. By looking at the cognitive classes as they appear across the four design phases that we can see what cognitive activities were used during these stages. This gives another dimension to the results from the cognitive coding scheme, shown in Figure 41.

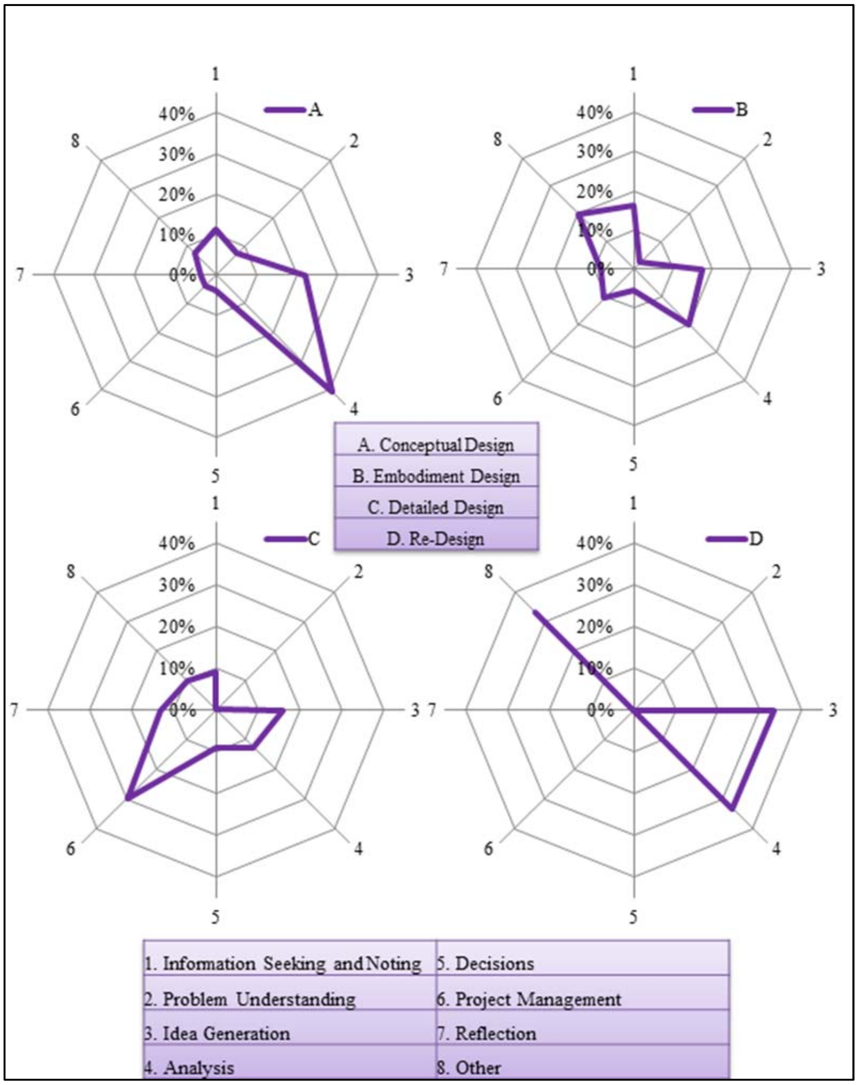


Figure 41: Professional Design Study 1 Cognitive Classes by Percent in Design Phases

During the conceptual design phase, analysis is shown as having the highest relative frequency. This is surprising because analysis is expected to be seen more in the embodiment and detailed design phase. Analysis includes the cognitive codes estimates, assumptions, calculations, testing procedures, variables, and explanations. These types of cognitive activities usually appear later in the design process. As a professional he may have a reduced dependency on information seeking and noting and problem understanding cognitive activities because of resources and designer experience.

During the embodiment design phase the codes seem to be even between information seeking and noting, idea generation, analysis and other. This is the second largest design phase in terms of design segments (following detail design). The detail design process (which spanned more than one year) is mostly consumed with the project management cognitive class. This is not surprising as it follows the trend that was shown in the previous section. There were only three design segments in the re-design phase and they are evenly split between idea generation, analysis, and other.

The difference in the patterns shown for each design phase is significant because it shows what he was thinking about at the different parts of the design process. He was not always focused on the same types of activities.

6.3 Concept Codes

31 concepts were tracked in the professionals' design journals that came from 682 design segments recorded. These were not all actual concepts, but more like components. If he had been working on one system or subsystem at a time then the term concept may be more applicable. The 31 components that were tracked are shown in Table 79. As the only mechanical engineer on the project Leland was responsible for working on many components at a time. These are probably just a fraction of the total amount. The components names, descriptions, and definitions

were all considered and counted at the discretion and understanding of the author of this dissertation.

Table 79: Professional Design Study 1 Components List

Professional Design Study Components			
Camera(1)	Base Plate(9)	PCB(17)	SCB(25)
Collimator(2)	Vacuum Connections(10)	Wax Motor(18)	RTD(26)
DEB(3)	Fasteners(11)	Bolts(19)	PS Box(27)
Analog DEB(4)	Teflon Insulators(12)	End Plate(20)	CCD Fixture(28)
Power Supply(5)	Connectors(13)	Magnet(21)	Vibe Fixture(29)
Wire Cables(6)	Combinations of Components (14)	O-Rings(22)	FOV(30)
Aluminum Frame(7)	Relay Filters(15)	Pop Top(23)	Stiffener(31)
Top Rad Plate(8)	PDR(16)	Pegasus(24)	

The camera (1) component in Figure 42 found in 79 design segments and the cognitive codes that are part of the same design string are shown in the figure below. The x-axis values shown in the figure are the design session number, which is related to the concept. The y-axis shows the spread of the 36 cognitive codes. It is possible that there is more than one occurrence in the design session but it is only shown as one data point.

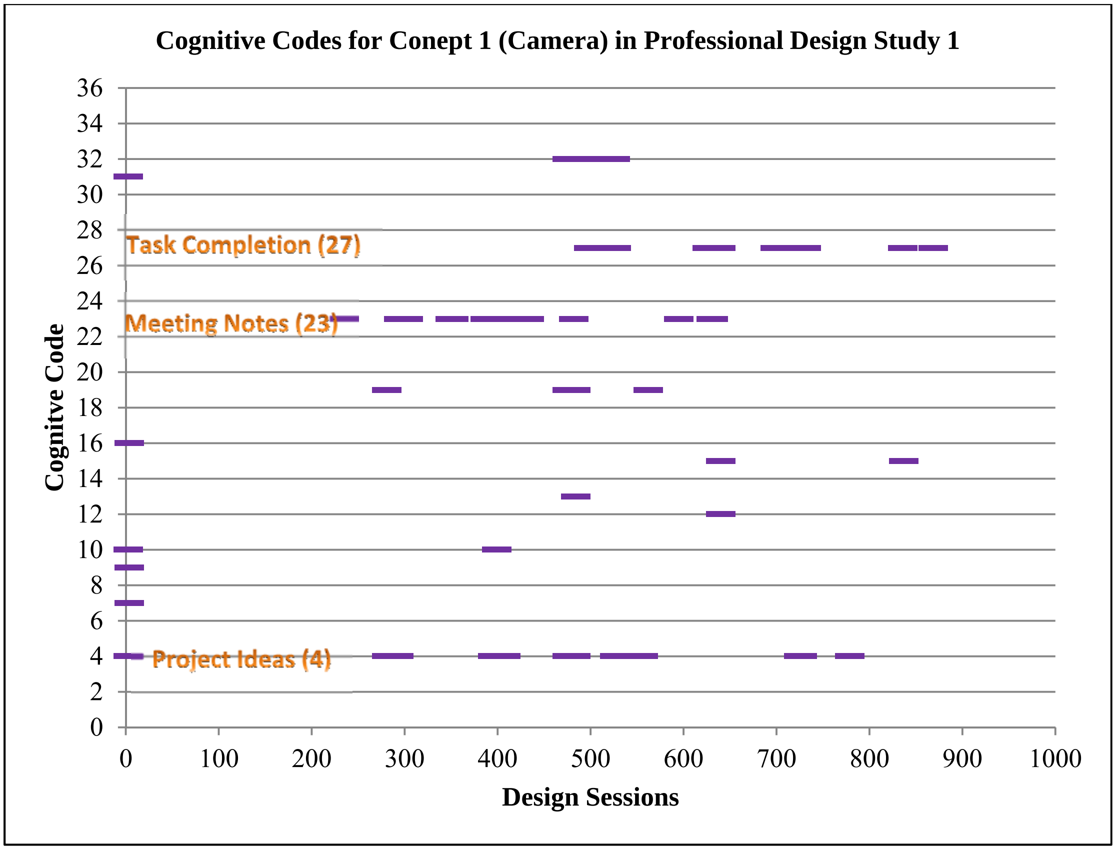


Figure 42: Concept 1 in Professional Design Study 1 Cognitive Codes

Figure 42 shows the different design sessions where concept 1 was mentioned. It also shows that task completion (27), meeting notes (23), and project ideas (4) cognitive codes were consistently found in relation to this concept across several design sessions.

Figure 43 provides the same information for concept 3, which is a subsystem with the name DEB. Design activity on the DEB was highest in mid-project. All activity was resolved before design session 800. This is not the case with the plot show in Figure 44. That chart presents the activity recorded for components discusses in combination. These components were likely to be functionally related. It's clear that activity on components in combination occurred more during the end of the design process.

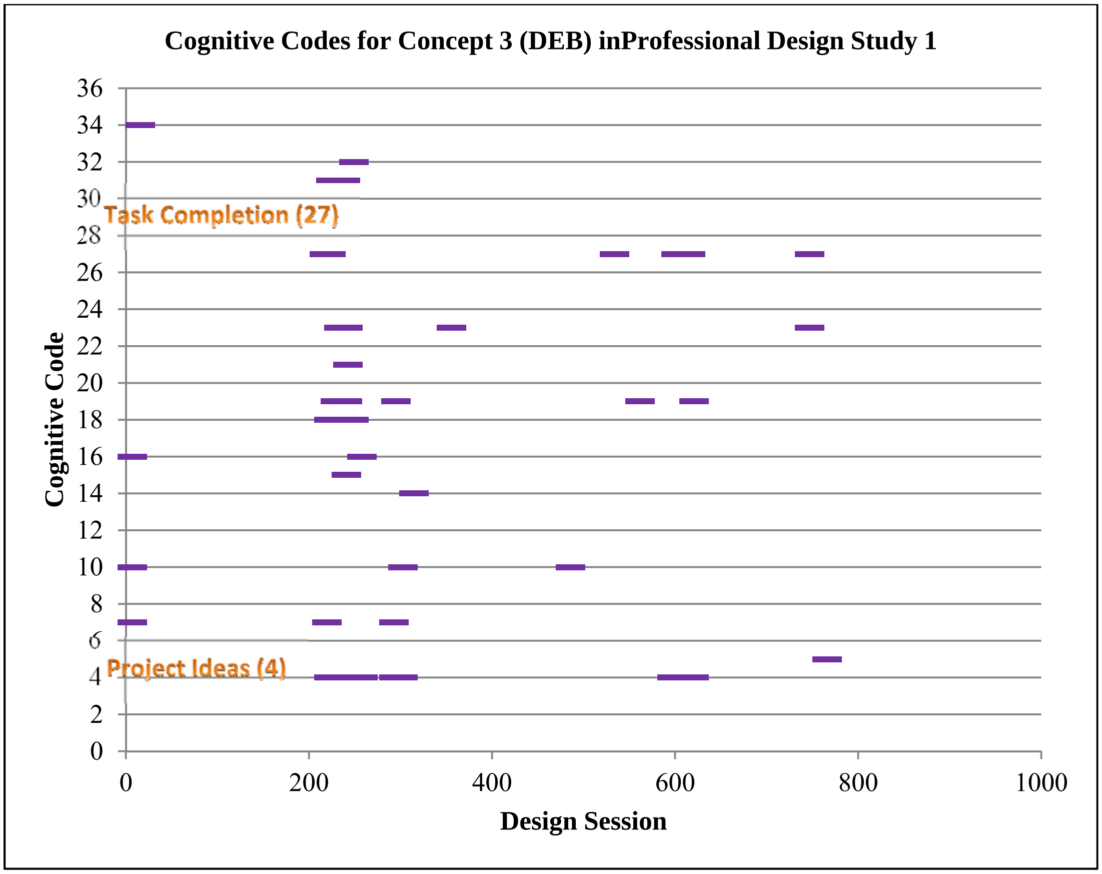


Figure 43: Concept 3 in Professional Design Study 1 Cognitive Codes

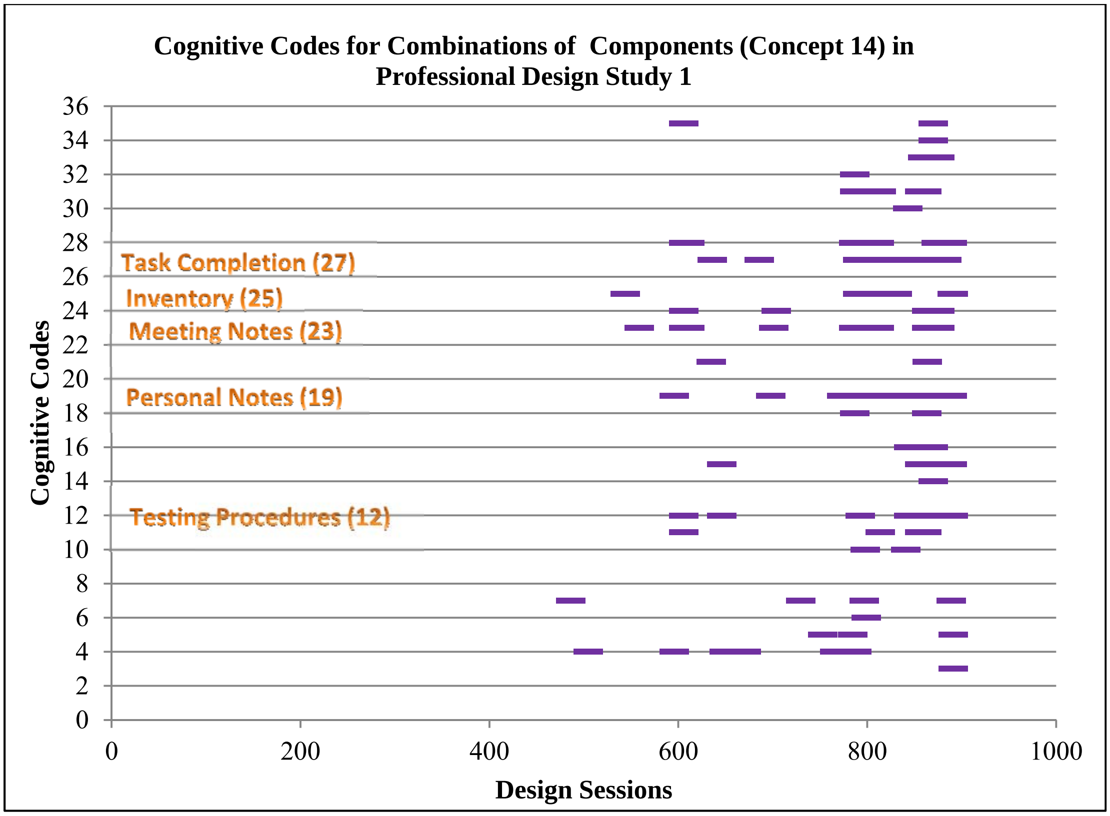


Figure 44: Activities for combinations of components (Concept 14) in Professional Design Study 1

6.4 Visual Representations

The visual coding results found in the professionals design journal as part of the design string are the subject of this section. The results are shown in Table 80. Most of the visuals found in the professionals design journal were sketches followed 2nd by CAD drawings. This is an important finding because it shows that sketching is still a very important part of the design process. The usefulness of sketches to the professional engineer is a testament to the fact that they are useful for solving large scale real world engineering problems. The professional engineer combined his use of sketches with CAD models. CAD models are shown here to be a useful tool for the design process.

Table 80: Professionals Design Study 1 Visual Code Results by Percent

Professional Design Study 1 Visual Code Information	
Visual Code	*Percent of Design Segments*
Sketch	10%
CAD	8%
Photo	0%
Simulation	0%
Line Drawing	0%
Electrical Drawing	1%
Chart/Table	6%
Free Body Diagram	0%
None	74%

6.5 Journaling Practices

It was expected that the journal would have a standard format and entries would be standard as well. An informal entry such as notes during meetings and also pasted-in information was not expected. The journal worked for the professional engineer based on his needs. The design journal actually resembled more of a hybrid lab notebook and personal diary.

Since the professional engineer may prefer to use other forms of recording things in addition to the design journal such loose leaf papers may be kept in another place.

It was astounding to see that the professional engineer kept a detailed account in the journals for such a lengthy design project. The level of detail included in the journals and in the calculations and repeated calculations done over and over were also a surprise because it was kept in meticulous style. Initially due to the nature of the project (US Government) it was assumed that the culture of the organization called for such details and structure but this assumption was wrong according to the professional engineer. He stated that design journals were not required by the company that he worked for but that was his personal practice that he has kept for many years.

During the exit- interview he stated that the most important reason he kept such meticulous design journals was to aide his memory, so he could remember what he did. As a mechanical engineer on this particular project he was in charge of all the design work on the mechanical components. That means that he had to essentially work on various design projects at the same time and the equipment he was working on was physically located in another country.

Having one place to come back to and reference all the previous work that he had done seemed to be a good idea for him. For a professional journal it was unexpected to see that at times he questioned his calculations, things other people told him, his reasoning, etc. He recorded the times when he felt that something just wasn't right with what he was doing. Then he gathered more information and came back and tried it again, which shows the iterative nature of design.

The professional engineer agreed to participate in an interview about his design journaling practices that was videotaped after the design journals were coded on site. The questions were a result of what was found in the design journals and also basic questions about his job at the time he was recording in the design journal. The answers to the exit interview questions pertaining to design process are shown in Table 81.

Table 81: Professional Designer Interview Question Responses (Exact Quotes) - Design Process

Design Process
1. How did you learn about the design process?
a. I used to work for major corporations before I came here. I actually worked in engineering before I got my bachelor's degree. Yes oh yes. I worked at nuclear power plants and I learned part of the engineer design process there. Then at school for bachelors and masters and then after school I learned the process via industry wise.
2. In the journals did you follow certain steps in the design process?
a. Yes, very detailed. The process that I go through I am very detailed oriented. It is a step-by-step process for me. I come up with several ideas and work through the process and see which one will be better and more beneficial than optimize the situation. Obviously a lot of feedback from other people as well.

The answers to the exit interview questions pertaining to design journals are shown in Table 82.

Table 82: Professional Designer Interview Question Responses (Exact Quotes) - Design Journals

Design Journals
1. Did your employer require a design journal? *Yes, but I've always done design journals. The 1st corporation that I worked for post college I started a design journal my 1st or 2nd day of work and have been doing them ever since.*
2. Did your colleagues use design journals? *Yes*
3. Have you ever ripped a page out of a design journal? *No, I have never ripped a page out of a design journal*
4. What benefits did you gain from using the journal?
a. Lots of benefits. I have my memory right there so everything is documented, especially working on something like a satellite it is very important if there is an error somewhere you can go back and take a look at things. And so to justify why you did something with a reason behind it not just making a change for making change sake. Also for memory sake. On other projects I have done work and not remembered it 6 weeks after I did it and because I had the CAD drawings, I had taken pictures, I could go back and see what I have done. I've done so many projects over my lifetime that sometimes things just run together. I've found that if I can document it, I can't remember it.
5. Do you feel the time was well spent making the journal? *Absolutely*
6. What are your thoughts about engineers and or students using journal today with all the things that have to capture our attention and so many details at one time and because of the new technology and all the things that students have to use?
a. I would still recommend journals, either e-journal or book type journal. I don't see how you can get around it. Even though one of the key uses was for patent use. That may not be important in the future with the new patent laws in place. It is still important to document everything. If you go to any of the Dilbert cartoons there is always comments about oh no we have to document that. So you have to document.
7. When did you make your entries in your journal?
a. Probably pre, during, and post. If I had to do some analysis I would probably write down some basic formulas in my journal and maybe do a couple of quick calculations. Meetings I always took notes during meetings and post meetings I would try to document things that were said. Sometimes I would write it there in handwriting and sometimes I would type it up and post it in my journal and also send it for distribution as well.

8. How do you encourage your students to use journals? *They will do it.*
   a. *It's part of their grade*
   b. *I check the journals*
   c. *Weekly*
   d. *Three check marks during the week*
   e. *They have to get the check mark*
9. How long have your students been using journals? *Since I've been teaching which hasn't been a long time*
10. How do you introduce/guidelines for journals to the students?
    a. *For the junior level course we have a list of items that we would like our students to put into the journals. It is the same thing for the senior level journal but the seniors only do one journal. Essentially anything you say, do, have a meeting, discuss, draw, sketch, anything you do that's related to your design project put it into your journal. So that's everything.*
11. When you ended this 3rd journal was that the end of project? *Yes, I vaguely remember entering one item into the journal and that was post project when it crashed into the Indian Ocean., numerous years later when it came back into orbit.*

Mr. Engel did not have to write a design journal. He was not required but because of his previous experiences with making a design journal he understood the importance of creating this records and what the benefits were for him. The main benefit he mentioned was to aid his memory so that he wouldn't have to repeat work. Since he was working on several projects at one time it was important for him to stay organized and the design journal was a tool for him to do that. He was not wasting his time by creating the design journal; it probably helped to make him a more efficient engineer.

6.6 Conclusions

The expectation for cognitive coding of a professional's design journal was that there would be more details and higher variety in the type of entries than previously found within the students' design journals.

The results show that:

- The majority of the professionals design journal was spent on detail design that shows the importance of this design phase for professional engineering.
- The high frequency of the codes in the project management and idea generation class shown in Figure 31 shows that these classes are essential to the professionals design process.
- Project management class of codes stand out as the highest overall percentage as shown in Figure 33 which reiterates the need for basic management skills as a mechanical engineer.
- Figure 41 shows how the cognitive activities in the different design phases are different, from what is reveals the dynamic diversity in design thinking throughout the different parts of the design process.
- According to the professional engineer who is now a professor at Penn State University students will use design journals in a design course given proper encouragement and regular constructive feedback. It is important for students using a design journal as a required part of a course to know what the professor will be checking for inside the journals.

What was most impressive was careful attention to detail and ownership (signatures included a lot with the date) of the work recorded in the journal. It is visible that he was dedicated to the project and doing it right, on time, and on budget, etc. His integrity of person and profession is evident through his design journals. His work is held in the highest regard as the work of a real professional mechanical engineer. He didn’t work for himself; he was dedicated to the mission. He followed a process, and he did not diverge or cut corners during that process.

Making comparisons with the students from Student Design Study 3 is the subject of the next chapter.

Chapter 7: Comparing Students with Professionals

The benefit of having access to the journals of a professional mechanical engineer is that comparisons can be made between the journaling behavior of students and the professional. Comparisons are made with respect to journaling behavior. There are differences in the data. The professional was working on a much longer, more complex project than the students. The student projects were done over a shorter time period and students were given a particular process to follow.

7.1 Comparing Students with Professionals Patterns of Journaling Behavior

Figure 45 and Figure 46 compares the average cognitive code distribution from the 9 students in Student Design Study 3 with the Professional Design Study 1 cognitive code results. The Student Design Study 3 averages are over the 9 students in the study and the professionals are from this data alone.

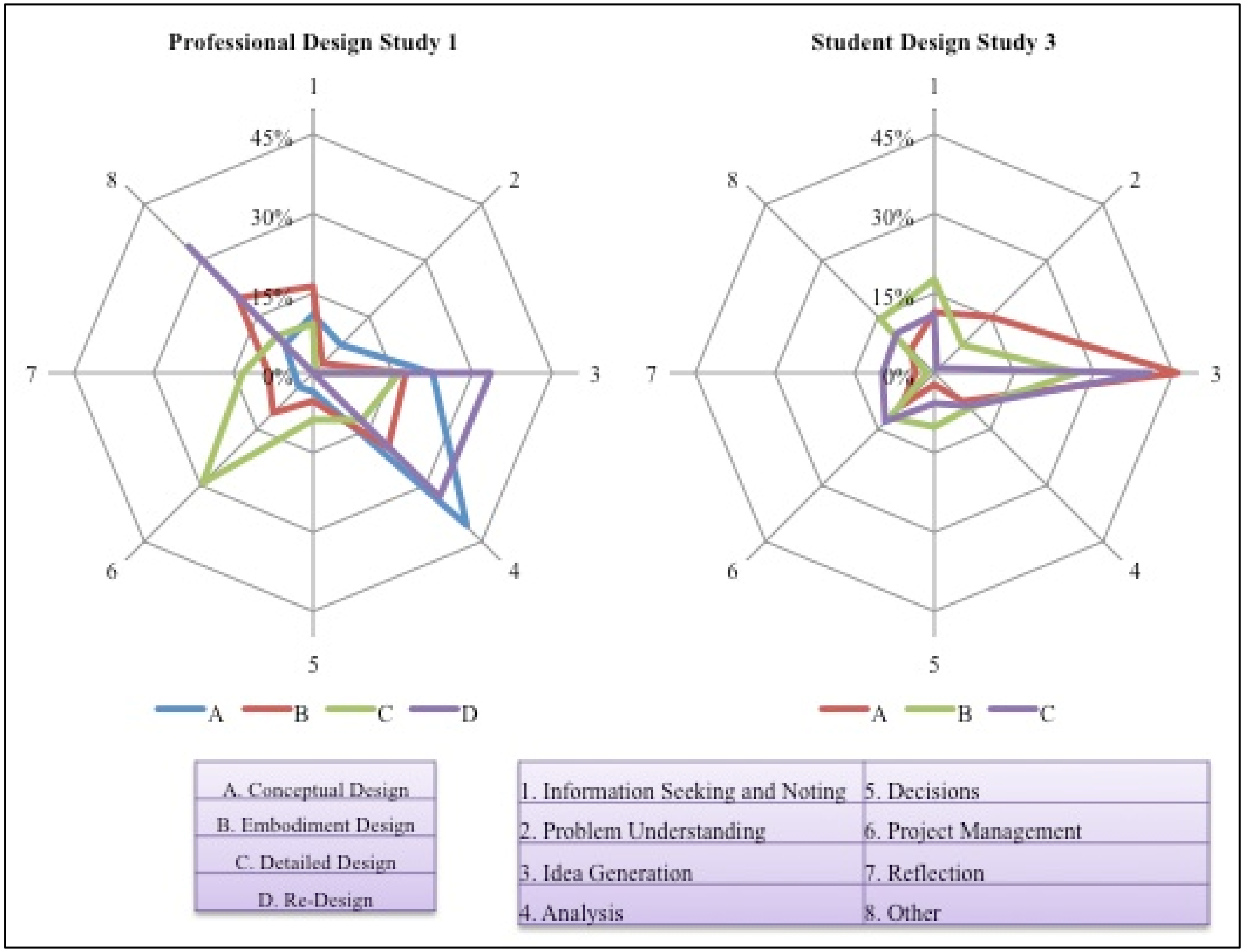


Figure 45: Comparison of Cognitive Class between Student Design Study 3 and Professional Design Study

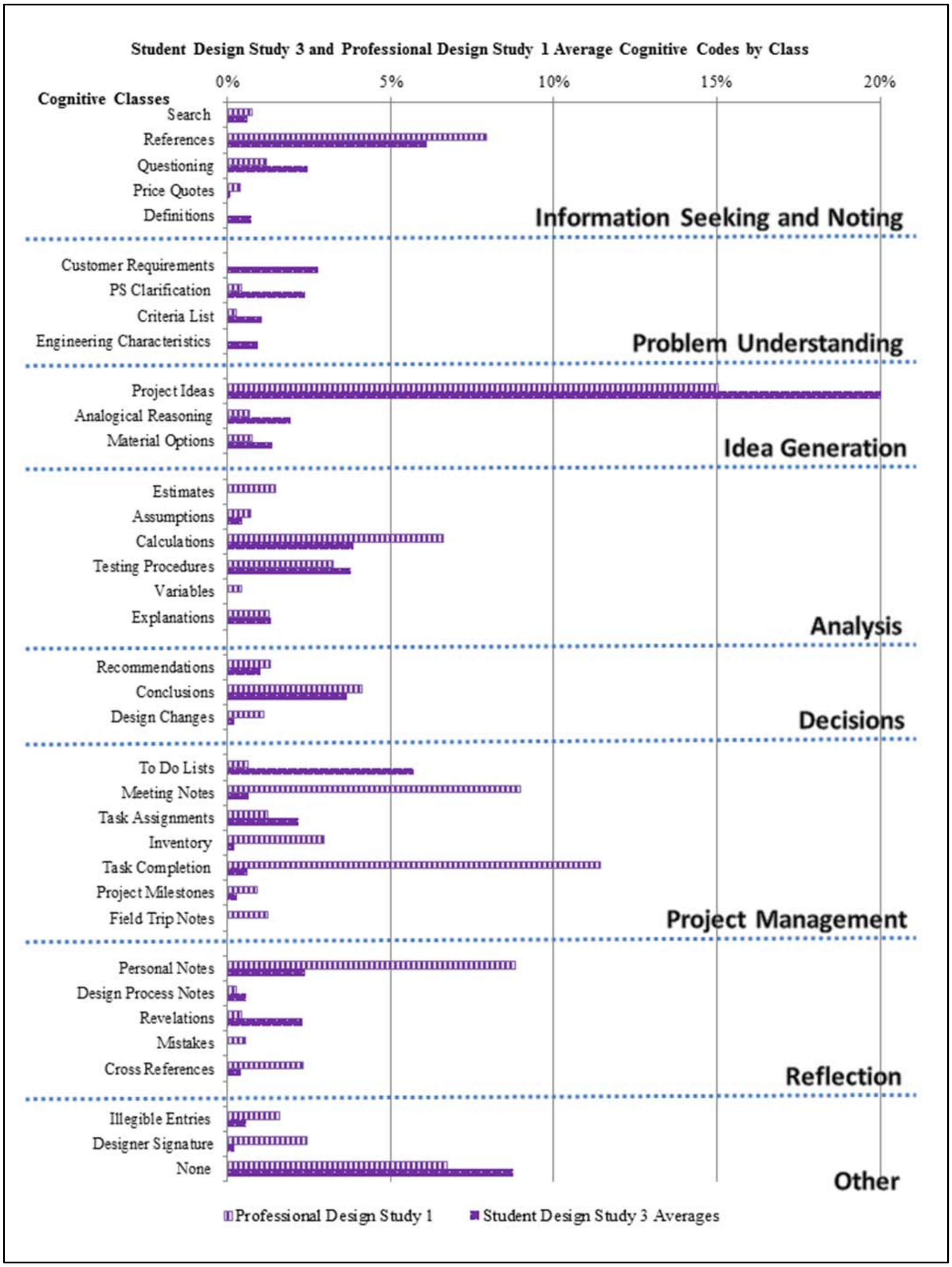


Figure 46: Comparisons of Cognitive Codes between Student Design Study 3 and Professional Design Study 1

- Information seeking and noting class codes are all less than 10% for both the students and the professional. The cognitive codes within this class only show 1-3% differences which mean that the behavior of the students in this class is similar to the professional.
- Problem understanding class shows that the students utilized these cognitive activities far more than the professional. This is not surprising given the student's low level of design knowledge and the professional's higher level of design knowledge.
- In the idea generation class the student's average for project ideas actually goes up to 37% which is cut off in the figure to expand the smaller percentage classes. For both the students and the professional this class has the highest overall frequency. The professional's average for idea project ideas is about 15%. Analogical reasoning and material options are similar for the student's and the professional.
- Analysis class codes are comparable between the students and the professionals; the only difference is shown in the cognitive code "variables". The students were found to have very few coded segments that included estimates. One difference may be the higher complexity and the longer length of the professional's project.
- Decisions class frequency is also similar between the students and the professional. The student's average for design changes is low and this is expected because of the short time of the design course. Leland was also very meticulous in his note taking especially when he made mistakes which may be the result of professional experience.

- A high amount of variation is shown in the project management cognitive class. Project management was very important to the professional engineer and not as much to the students (with the exception of to do lists). A high amount of to do list in the students' design journals was expected because the students are juggling many commitments a short list is a fast way to track a team member's responsibilities for this design project. The students were working in teams and the project management responsibilities may not have been shared equally. The students also have to learn to manage multiple projects like the professional was doing because other senior level engineering courses also require team projects.
- The reflection class shows that the student's did not use these codes that much. The professional made lots of notes to himself throughout his design journal. The students were probably not as concerned with making these types of reflections in their design journals.
- The other class is telling, because it could mean that there are some journal record types missing from this cognitive coding scheme. It could also reveal that some of the students don't know how to properly use a design journal.

7.2 Cognitive Behavior

Cognitive coding data has been displayed in many different ways in this work. One interesting method of summarizing the cognitive behavior implied by journal records is the plotting of the relative number of journal segments by cognitive code classes established in this work. These are presented as spider plots in Figure 47 through Figure 56 (from Student Design Study 3 and Professional Design Study 1).

Figure 47 is interesting because during the detail design phase this student was reflecting.

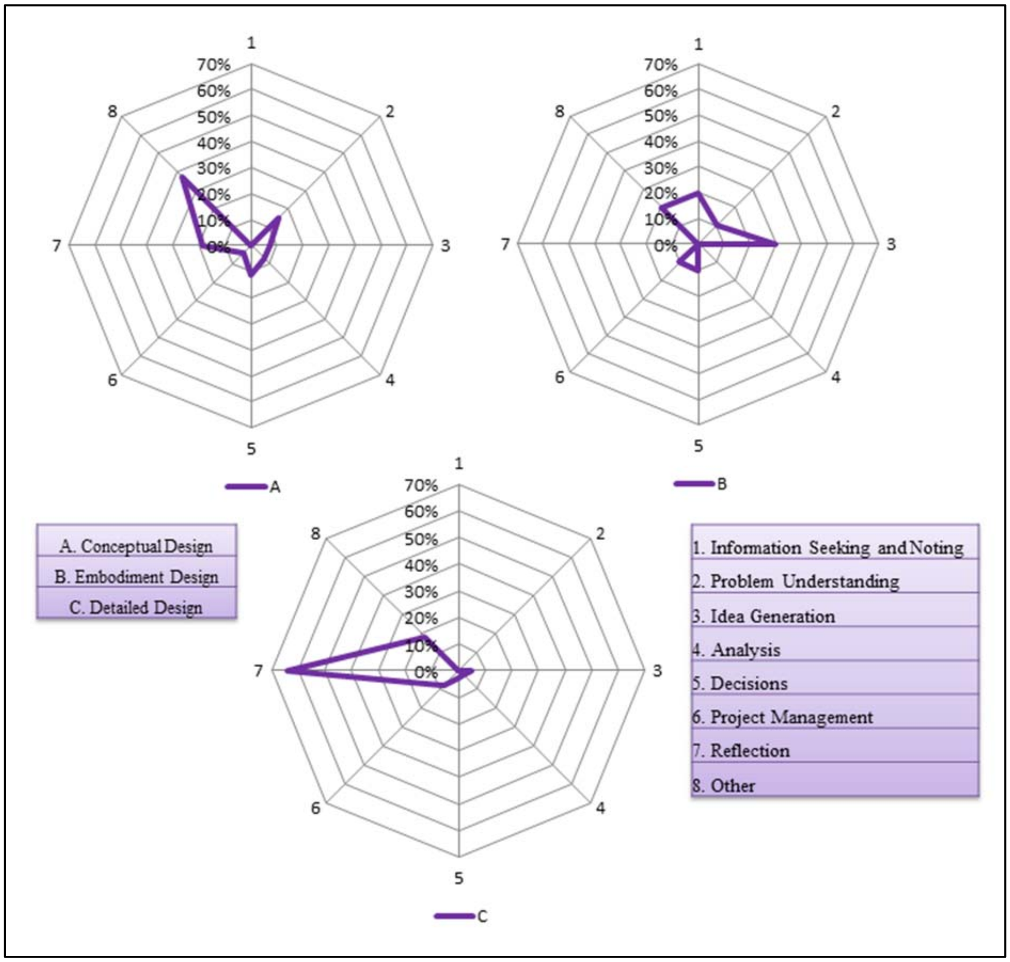


Figure 47: SDS3 Journal 1 Cognitive Classes by Design Phase

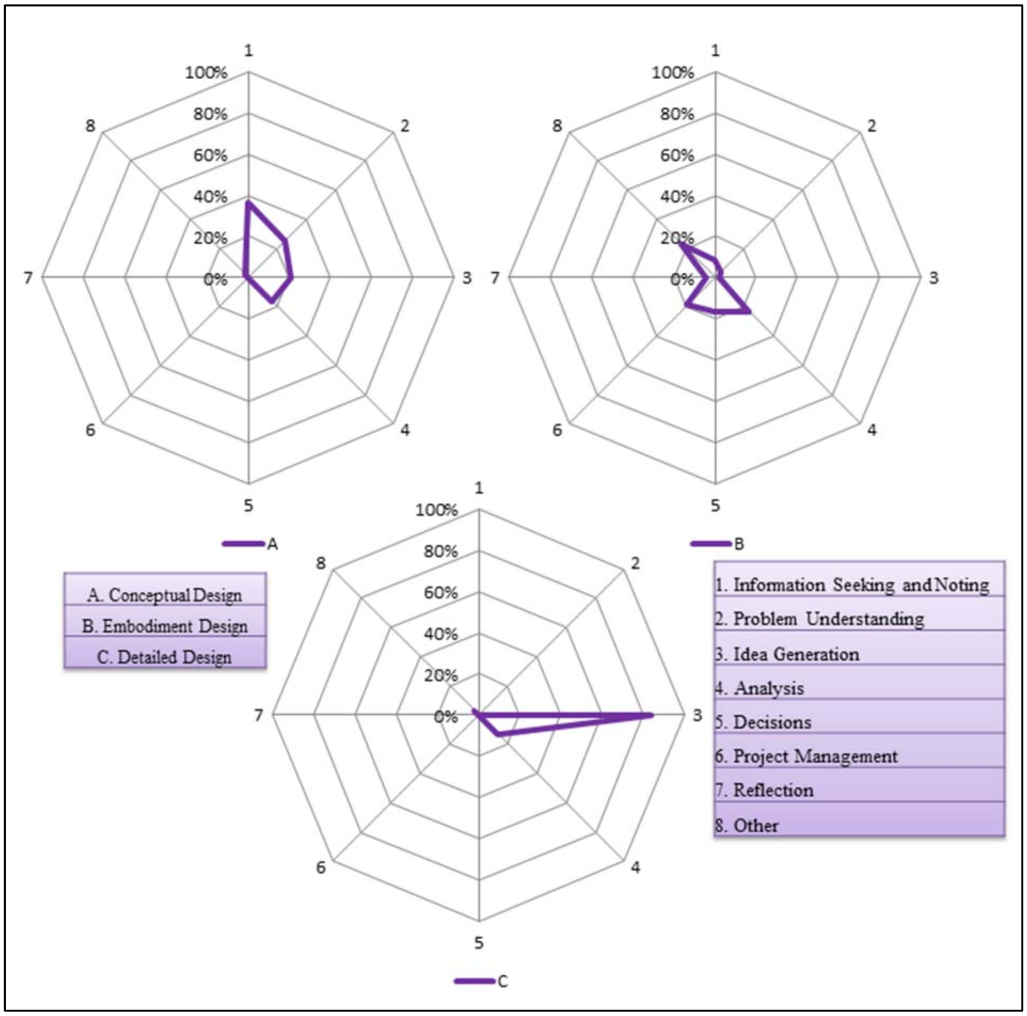


Figure 48: SDS3 Journal 3 Cognitive Classes by Design Phase

Conceptual design and embodiment design are almost mirrored in Figure 49 for idea generation. Embodiment design does require unique solutions which may iterate back to idea generation; this design journal shows the iterative nature of the design process.

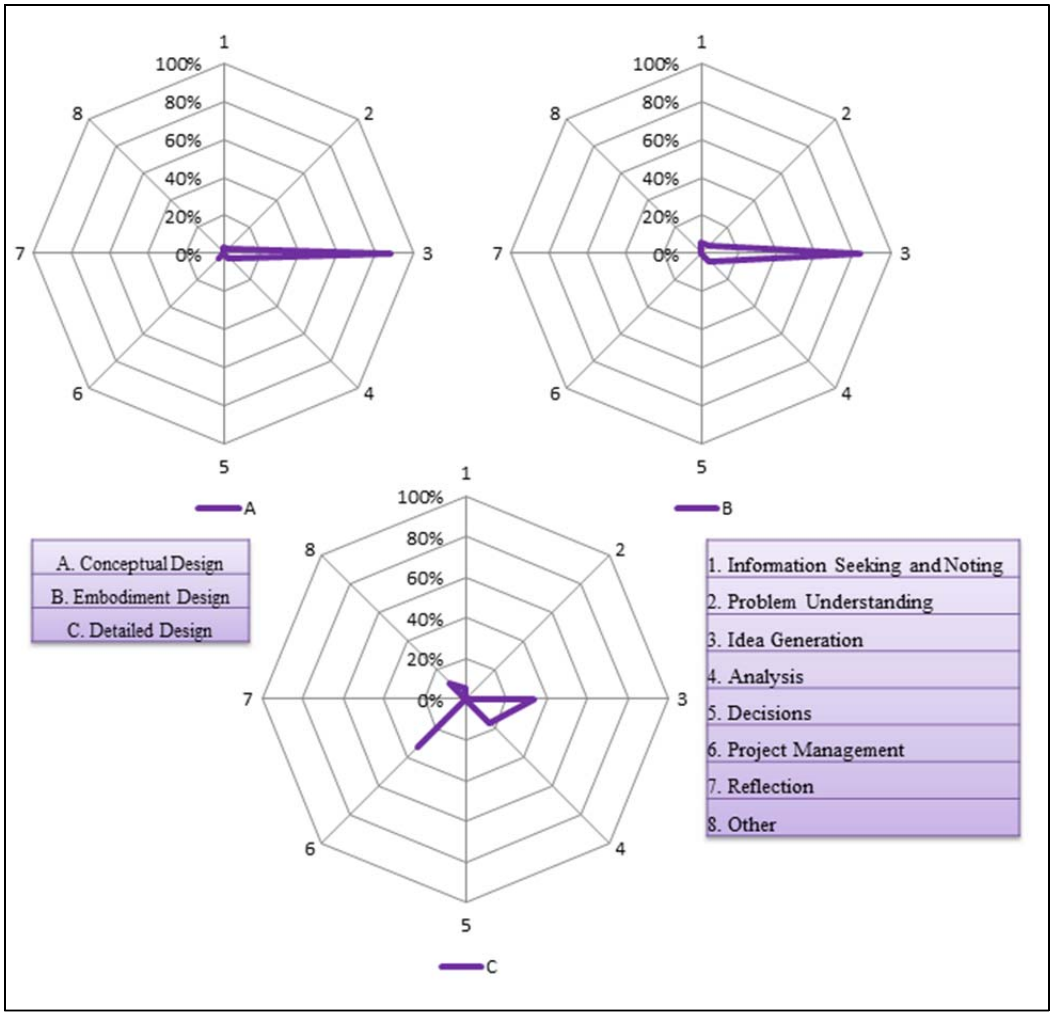


Figure 49: SDS3 Journal 5 Cognitive Classes by Design Phase

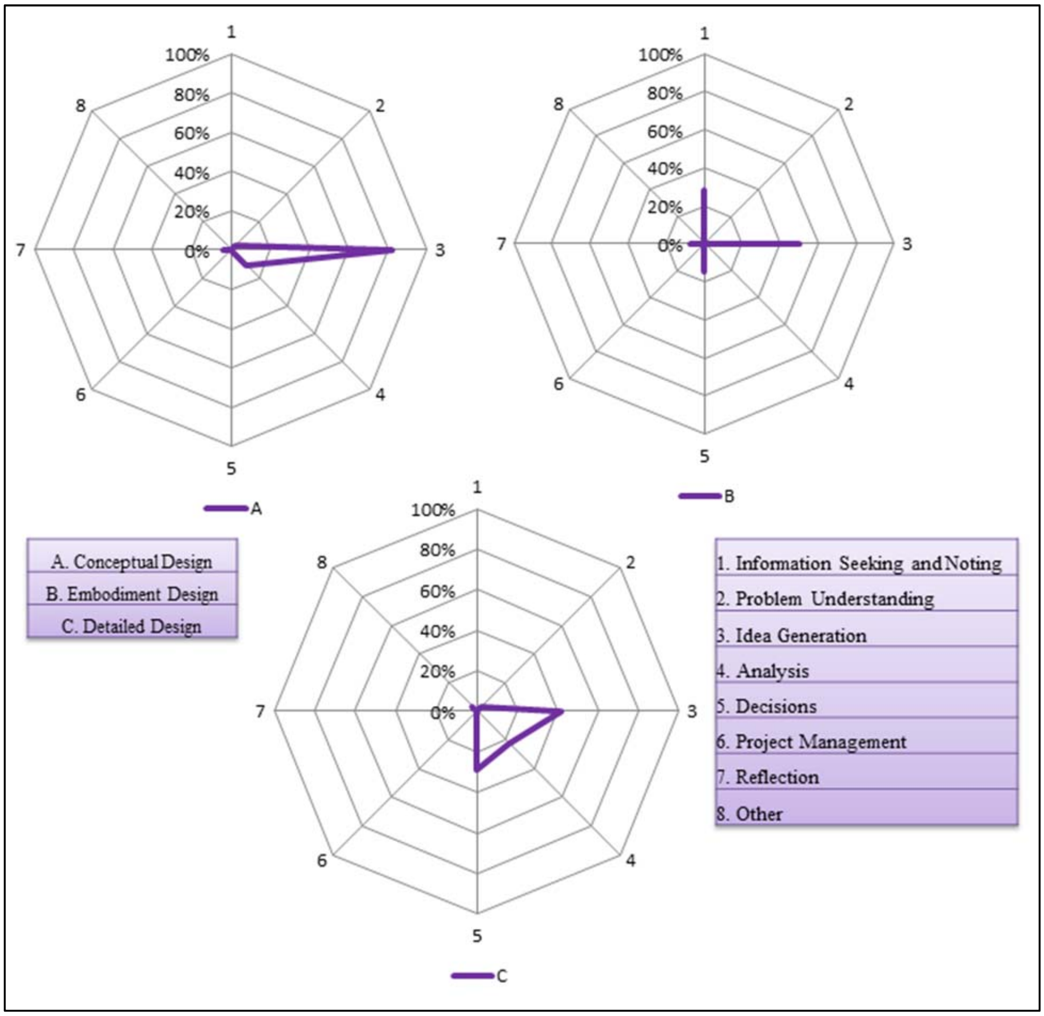


Figure 50: SDS3 Journal 6 Cognitive Classes by Design Phase

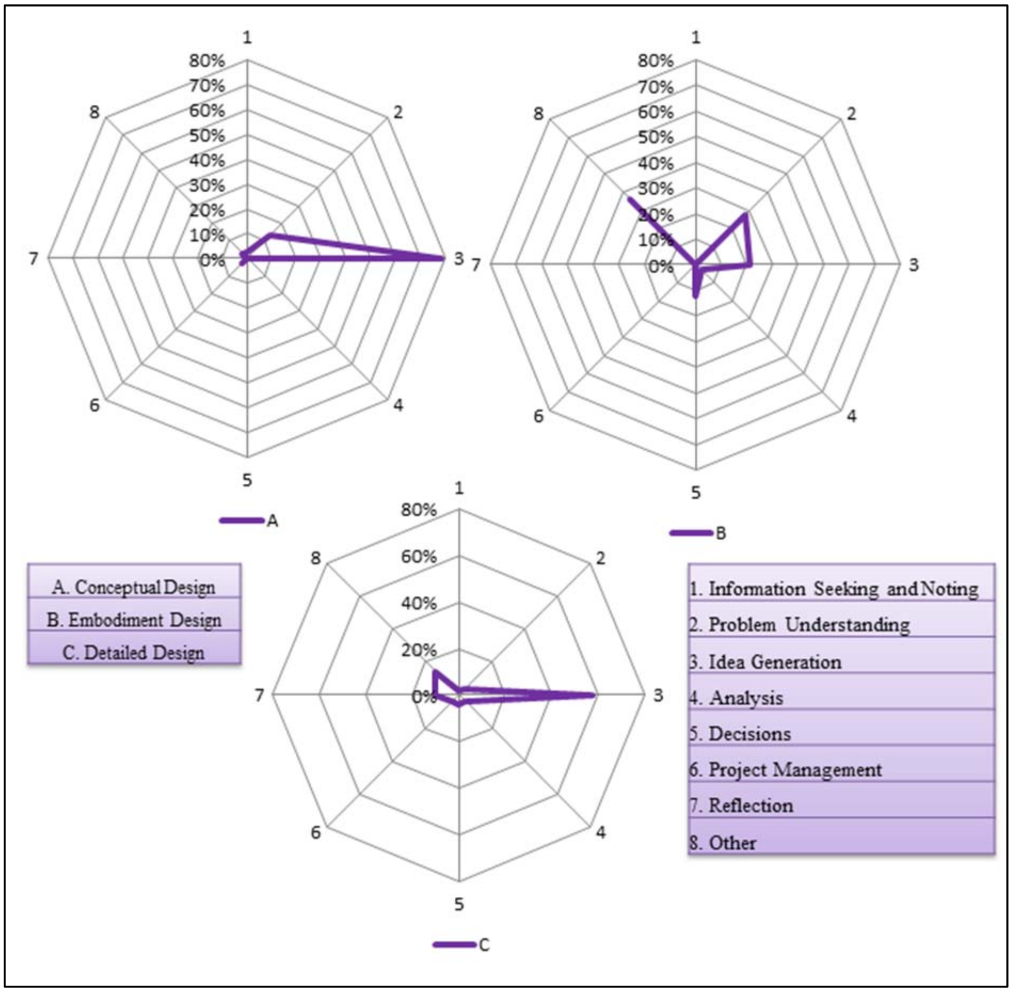


Figure 51: SDS3 Journal 7 Cognitive Classes by Design Phase

The student shown in Figure 52 was managing the project and it would not be surprising if they had a formal title as team project manager. The fact the highest percentages in the project management class spans across all three design phases gives witness to what this journal writer was doing all semester long.

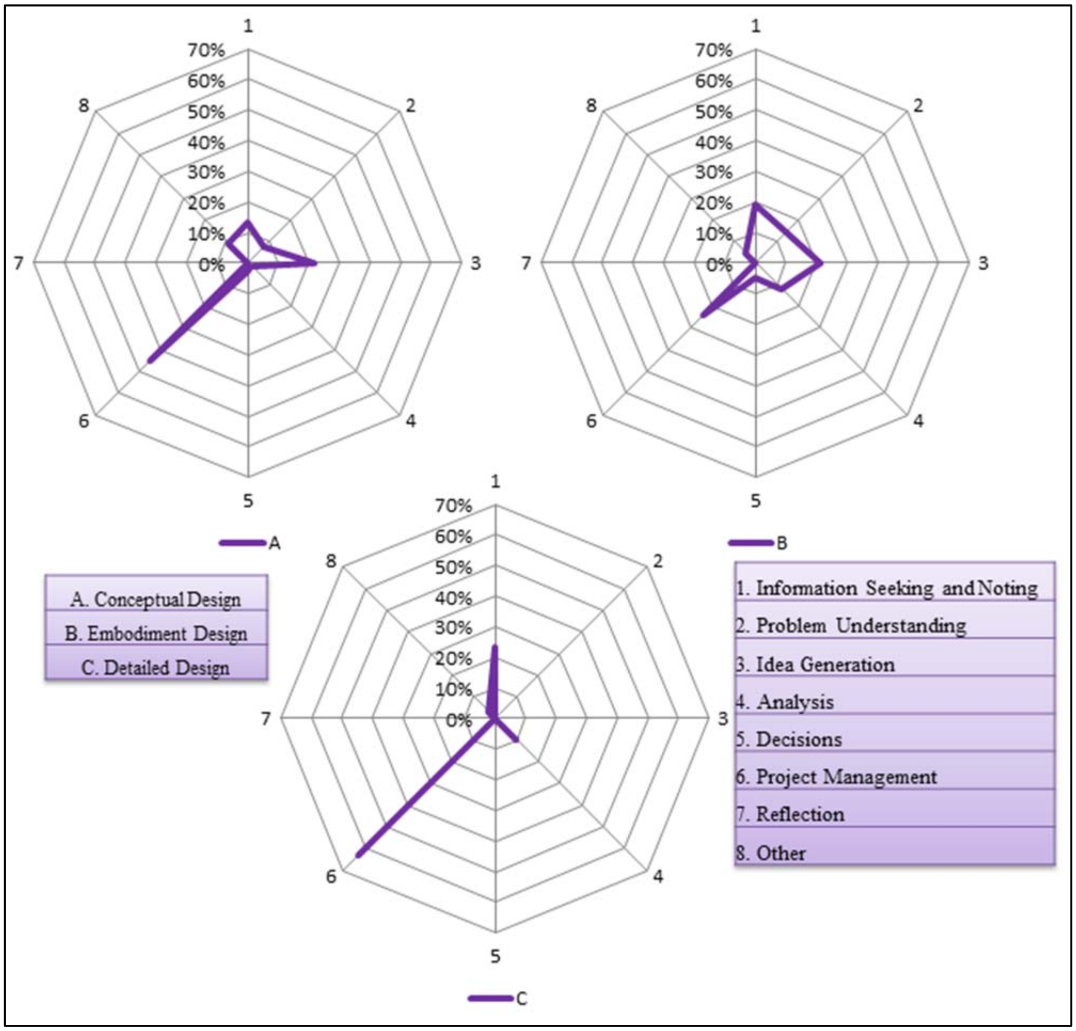


Figure 52: SDS3 Journal 9 Cognitive Classes by Design Phase

Figure 53 only shows one design phase: conceptual design. This student was either only using the design journal during conceptual design exercises or the conceptual design phase for this group may have taken longer than anticipated. The case could also be that this student was not a very active journal writer after the conceptual design phase of the project.

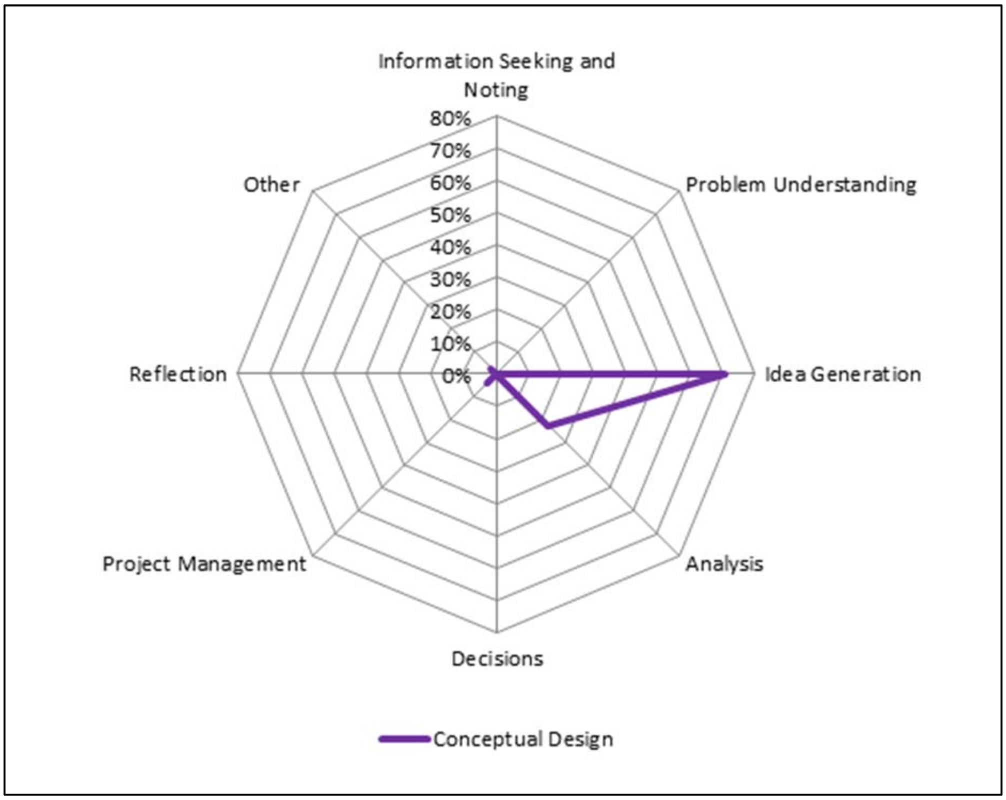


Figure 53: SDS3 Journal 10 Cognitive Classes by Design Phase

Figure 54 shows is a trend that is similar to what is expected to see in professionals design journals, a high amount of time spent at the beginning (conceptual design) actually understanding the problem before jumping in to come up with solutions. Research shows that professionals usually spend more time in the problem understanding or project realization (as Atman) calls it than the students would or do. This journal writer was also generating a high amount of ideas during the detailed design phase.

The student in Figure 54 was generating most of their ideas during the detailed design phase. This is unexpected because idea generation traditionally happens during the conceptual design phase of the design process.

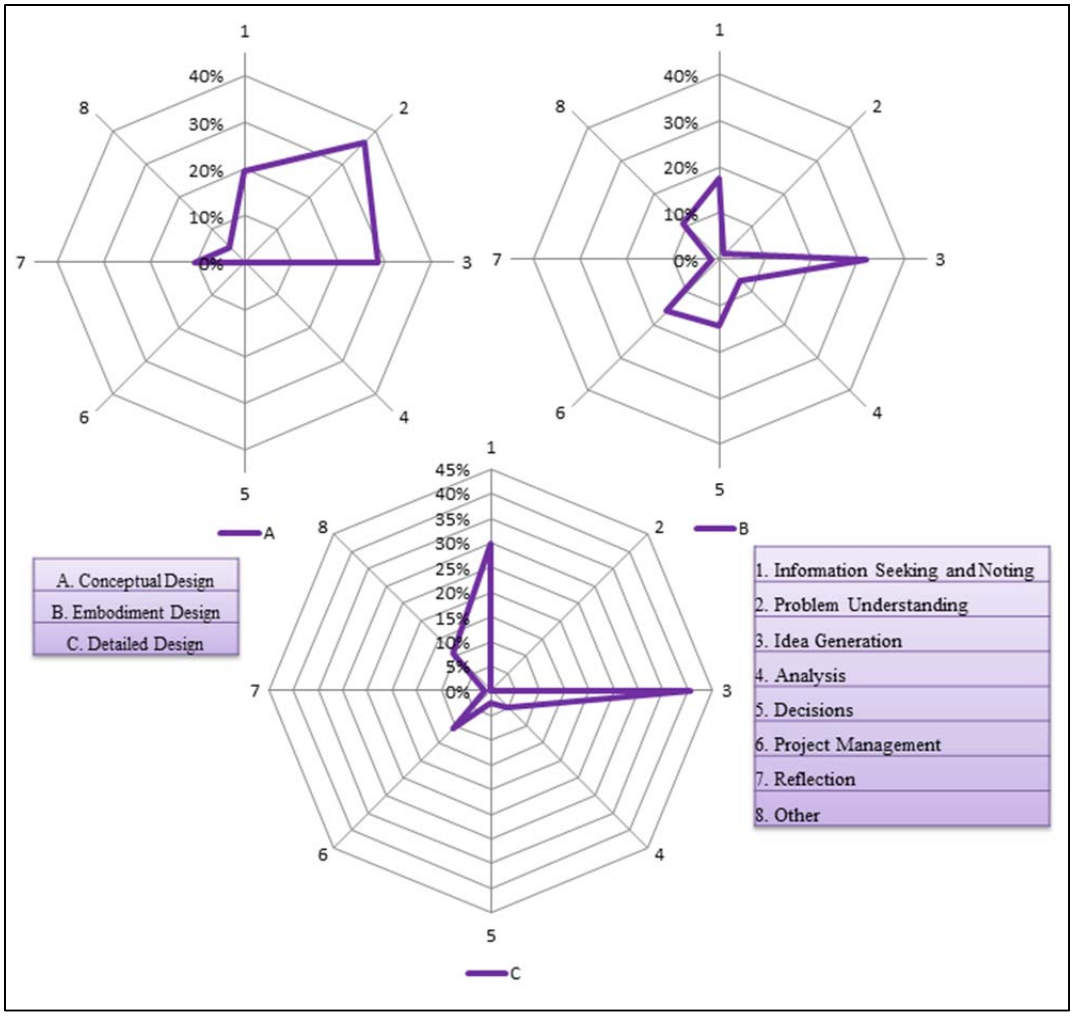


Figure 54: SDS3 Journal 14 Cognitive Classes by Design Phase

The student shown in Figure 55 leads to the following questions: What information or types of information was this person seeking during the embodiment design phase? Why are so many ideas generated during detailed design? Is that just an example of the iterative nature of the design process?

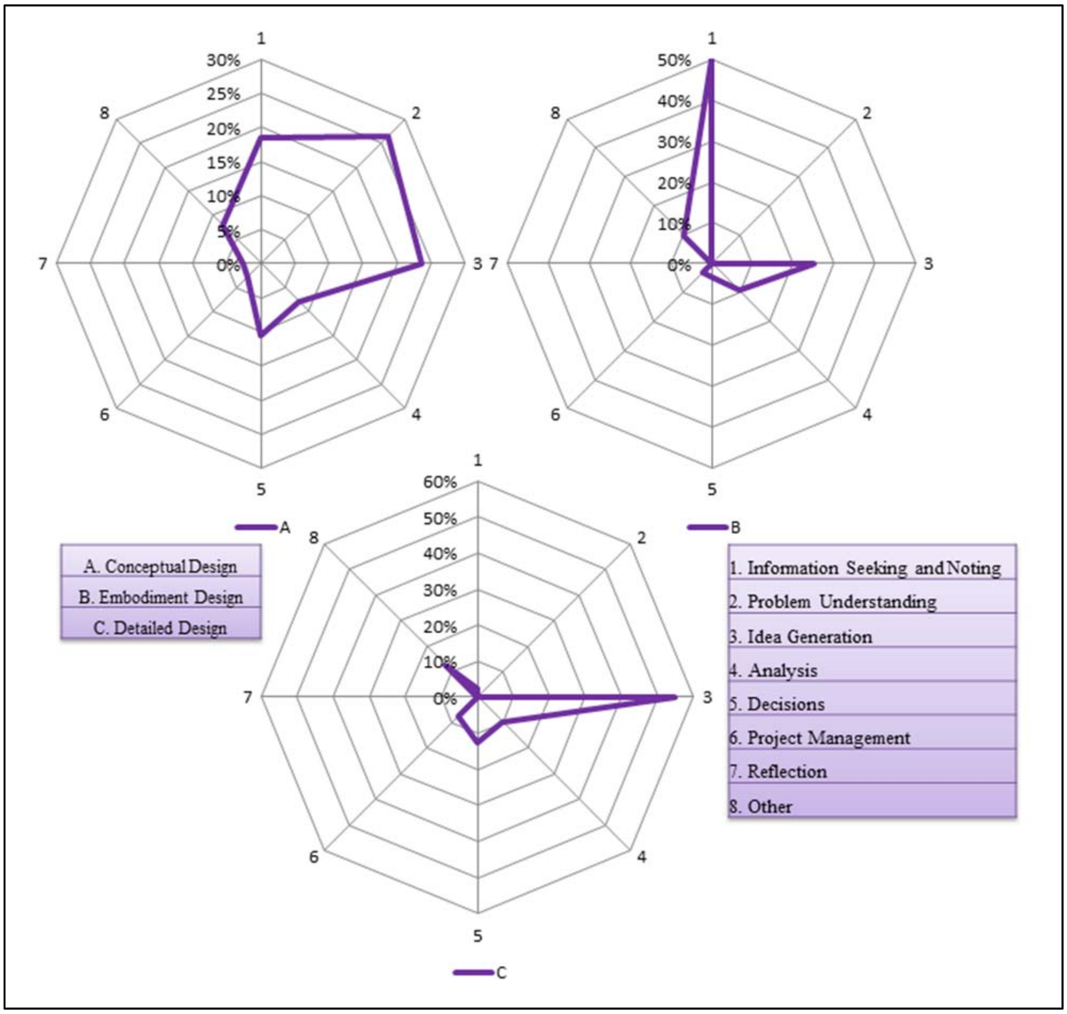


Figure 55: SDS3 Journal 15 Cognitive Classes by Design Phase

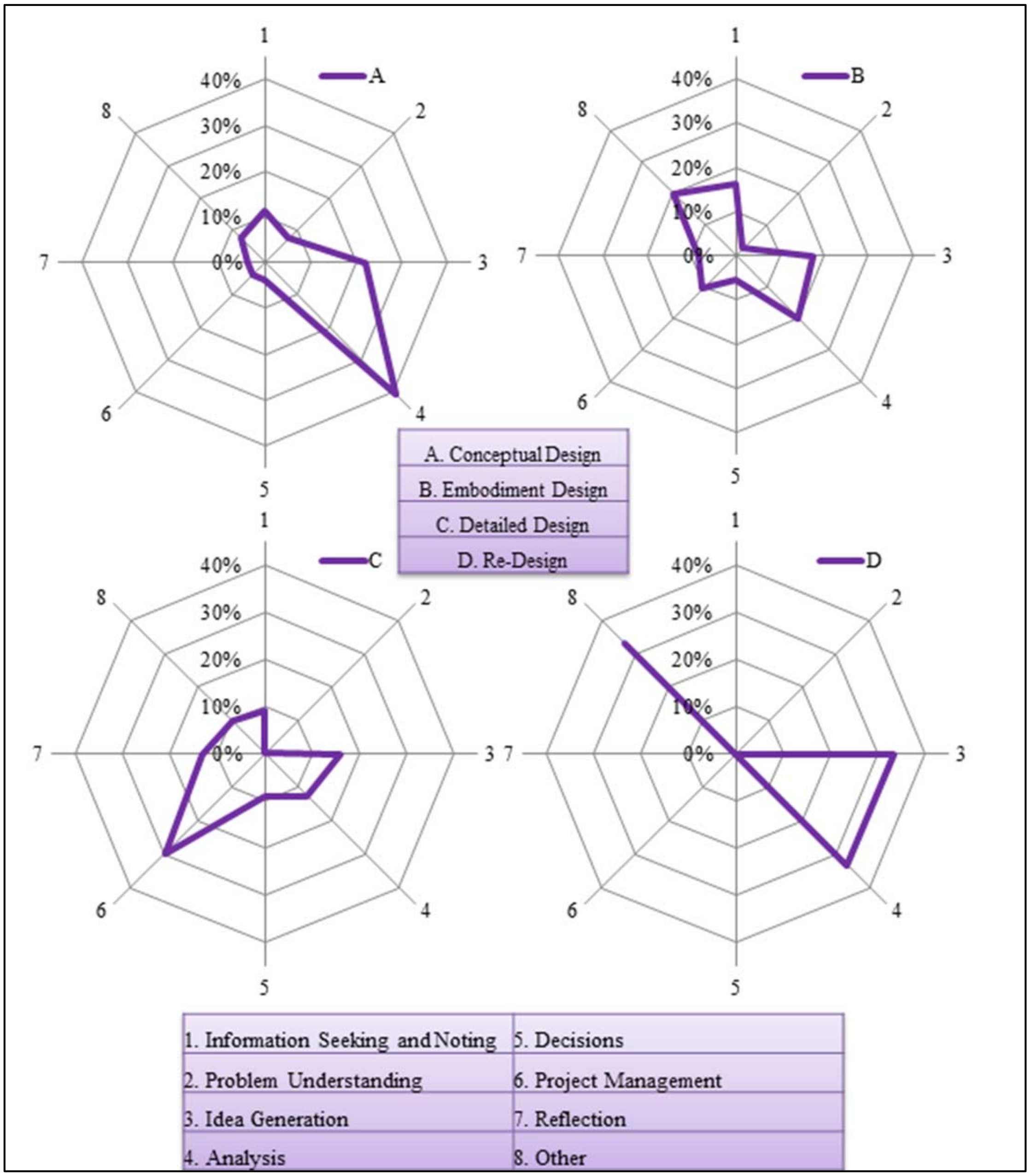


Figure 56: Professional Design Study 1 Cognitive Classes by Design Phase

7.3 Conclusions

Some of the conclusions found from the comparisons in this chapter are:

- One of the benefits of doing the journaling in this non-prescriptive way is to see if there were differences in journaling behavior. The differences in the behavior can clearly be seen earlier this section.
- This research allowed us to see patterns of behavior in different design phases and also it appears to show differences in personality.

Chapter 8: Conclusions and Future Work

The goal of this work is the development of a cognitive coding scheme that can be applied to journals written during a design process. The longer-term objective is to uncover the type of thinking activity that occurs during design and find patterns of activity. We cannot directly observe the cognitive activity during design but we can study what is implied by the act of recording in a design journal. The journals studied here included one set from a professional designer and twenty-eight individual journals from students in a mechanical engineering capstone design course. Students were asked to use their journals to record information (according to a set of general guidelines) during their design process without prescribing what exactly to record. This approach uncovered similarities and differences in journaling behavior among individuals and teams. The approach of this dissertation was data-driven quantitative analysis of design documentation supplemented with analysis of qualitative information from study subjects.

8.1 Research Questions Results

This work's goal was to investigate the following four research questions:

1. How can cognitive activities be identified from studying engineering design documentation from the classroom and in professional practice?

- The comprehensive cognitive coding scheme is effective for use on design documentation (36 cognitive codes and 8 cognitive classes) for both students and a professional design engineer.

- The design string allows the coded journal data to be analyzed quantitatively.
- The validation process demonstrated that the proposed cognitive coding scheme is useful in producing the same type of design research results as found previously by Atman et al. [4] and Jain and Sobek [29].
- Inter coder reliability testing provided good agreement on two journals and fair agreement on a third, indicating that there may be variation by journal writer or that the training process should be improved.

2. What cognitive activity sequences exist to aid designers in developing an enhanced understanding of design problems?

- This research shows patterns of behavior during different design phases and demonstrated how to summarize differences by coding class. Sequences of codes were not directly addressed in this work.
- The voluntary use of design journals for an entire semester can reveal useful information about how students' progress through the design process
- Project management journal entries were very important for the professional engineer whereas project ideas were most important for the students
- Detail design phase codes were highest for the professional engineer whereas conceptual design codes were found to be the most frequent category for the students

3. How do engineering design students respond to using hand written design journals within a capstone design course and why?

- Favorable attitudes resulted from the students using the design journals and they seemed to realize the benefits of having used them the entire semester.
- Differences in the frequency of reviewing the students' journals (administering the study) did not significantly affect the average activity densities between the UMD teams and Dr. Sobek's teams.

4. What can engineering design documentation reveal about participation within and between capstone design team members' design activities?

- Concept development (to the extent it is recorded) can be traced within a particular journal and the journals of members of the same team.
- Metrics were proposed to quantify the frequency of journal entries for a particular concept (the author's, other team members', and final team concept).
- The same or higher levels of participation in recording concept work are shown for the students in UMD Study1 when compared to Team S from Dr. Sobek. This is validation that the concept referencing metrics can be used with student's natural journaling habits

8.2 Study Limitations

This work's limitations are:

1. The sample sizes used in this dissertation are relative small and prevent strong conclusions from being made. Care is given in this document in reference to such conclusions.
2. This work analyzes the frequency of design journal entries and behavior but does not address the quality of the students design journal entries.
3. The majority of the results are drawn from students volunteering to journal during their design course for the study. Understanding the student's interests in design and journaling will layer another dimension to this work towards a whole picture of the designer.

8.3 Contributions of This Research

This dissertation makes the following contributions to the study of engineering design:

1. A cognitive coding scheme has been developed that can be used successfully used to explore the content of design journals.
2. Metrics for design journal analysis have been created. The concept referencing ratios and the activity density metrics show how team concepts are developed in the design journals and the level of activity within each design session.
3. This study supports implementing individual design journals in design courses. For faculty members wanting to implement these design journal metrics a few possibilities can be recommended: (1) weekly monitoring of design journal use is necessary, (2) journal coding can be limited to a few

codes or classes at (as opposed to the entire 36 code system), tracking cognitive classes at different parts of the design process would be practical, (3) Selecting some of the codes to assess design behavior during different parts of the design process; (4) Providing useful definitions of journaling entries for specific design phases and classes and providing a sample journal to students at the start of the class.

4. This work presents a way to see patterns in journaling behavior and student differences. It is hypothesized that different team roles may be shown through the student's journaling behavior.

8.4 Future Research

Future efforts can include:

- Investigating the sequences of cognitive codes as they appear in the design journals and comparing high-frequency sequences from the professional's journal to those of the students.
- Investigating the differences observed in journaling behavior to see if these differences are related to student personality, learn style, team role, or other relevant characteristics.
- Combining the cognitive coding scheme results with a design performance measure to understand the relationship between "good" design and cognitive activities. Creating a design performance measure that can effectively codify innovation at the early design. This will enable the cognitive coding scheme to increase understanding innovative design thinking.

- Studying the graphic entries in the design journals to identify the visual representations' roles in the design process. Investigating how the use and type of visual representations vary at different stages of the design process, and answering the question, "What does use of visual representations say about non-linguistic reliance during the design process?"
- Efforts toward creating a cognitive model of the engineering design process from an information processing view using the cognitive coding scheme as a starting point. Attempt to match the cognitive codes with current models of engineering design process to see if natural similarities exist.

Results from this dissertation provide a better understanding about differences between the journaling behavior of senior students in engineering design and a professional designer work on a multi-year project. The study generated vast amounts of quantitative data that will continue to provide research results into the future. Combining the results of this work with educational psychology can lead to the creation of tools that can improve how engineering design is implemented and taught. Results from this work can be used to facilitate future design documentation research, create better engineering design courses and provide improved design knowledge assessment tools.

Appendices

Cognitive Studies in Design: A Historical Perspective

A theory of design has not yet been widely agreed upon, although various prescriptive and descriptive models as well as stage and process models have been presented. This section presents a discussion of differing design perspectives from leaders in the field.

Simon- Design as a Science of the Artificial

Simon coined the term *satisficing* for general problem solving including design activities [100]. Satisficing has become a commonly accepted strategy in design and engineering. In the process the designer searches for the solution within a problem space, weaving in and out of knowledge states until a solution is found. In his book *The Sciences of the Artificial*, Simon (2001) asks the question: “Can there be artificial science or knowledge of artificial objects and phenomena?” (p. 3) Simon is asking if we can realize or be certain about things that exist in an artificial world, yet are used in the natural world to solve problems and create new designs. He claims that everyone who changes existing circumstances into preferred ones is designing. Design is focused on how things ought to be, compared to the natural sciences which focus on how things already are. He argues that the science of design is a legitimate field and his stand would support cognition research in engineering design such as this dissertation.

Simon claims that (at the time of writing his book [100], 1969) most engineering, business, and medical schools have gotten away from teaching design giving preference to subjects that (according to those in academia) are more intellectually challenging, analytical, and teachable. This has been done on the university level to gain more rapport within the campus academic circles.

Simon gives a substantial list of topics that should be included in a design curriculum. This list includes computational methods, representations of design problems, and the formal logic of design. Simon was a brilliant thinker who acknowledged that design is separate from the natural sciences, and called it a new science -- the *science of the artificial*. He proposed that this science is actually more important than the natural sciences. Simons hoped with his book to confirm to readers the proof he had for validating this field of study. Psychologically speaking, he shows how many people use their environment to create and survive, which is essentially the nature of design. Simon's work supports this current research as one of the first to create a foundation for design research and highlighting the important aspects of design as a science. The type research that Simon initially set to do in his early work in the social sciences was intended to promote the same demanding methodologies as the natural sciences [101]. Although here we are not proposing to agree completely with Simon's design as a science, in the context of our current goals his work is original, foundational, and relevant. In light of his standing within many academic communities it is tempting to conclude that scholars within various fields such as engineering, psychology, and economics would agree completely with him.

Visser- Design as Construction of Representations

In her book The *Cognitive Artifacts of Designing* Visser proposes a cognitive descriptive model of design to aid in understanding the cognitive aspects in the design process and to advance the education of designers [44]. According to Visser (2006) a definition of cognitive design research as "studies of design focusing on its cognitive aspects" which engineering design researchers refer to as "design thinking" (p. 1). She positions cognitive design research within the field of cognitive science. Visser claims, in her opinion, that design theory and cognition research began with Simon's (collaborating with Newell) work in 1972 [98]. This dissertation is cognitive design research and Visser's book offers a historical and interdisciplinary perspective on the field that is a more recent perspective on the history of design.

One drawback is that her book seems to be restraining the capacity of cognitive design research by only placing it within the cognitive science field. Design happens within many settings; therefore it is possible to include any research on cognitive operators while doing 'X' design activity in the field of cognitive design research. The theory of design that Visser (2006) proposes in her book is "design as a construction of representations" as opposed to simply problem solving (p. 1). Such representations are internal (mental representations) and external (verbal descriptions) and the latter she defines as cognitive artifacts (the former are by her definition cognitive artifacts). Representations are the results of the design process and are also considered artifacts because they are man-made. Therefore the resulting artifacts are external and internal as well as physical (trains, engines, homes, and power tools) and symbolic (software, systems, policies, or route plans). For the purpose of her book she refers to design as a purely cognitive activity including the methods, tasks, or steps that a designer uses. Furthermore, Visser (2006) views "designing as a cognitive activity rather than the designated professional status", which was first identified by

Simon[2] (p. 51) [102]. Visser (2006) adapts Simon's definition of a designer, as everyone "who changes existing circumstances into preferred ones are designers" (p. 50) [100]. She states that competent designers not only acquire formal knowledge from education and books but also through experiencing different kinds of design problems.

Visser presents a cognitive description of design in which she defines design as representing construction activities that include generation, transformation, and evaluation; all performed at the cognitive level. She defines constructions of representations as generation if memory was used as the main source of information. Generation involves the use of cognitive activities and operators such as information gathering which would generally occur at the beginning of the design process. Transformation is defined in terms of the type of transformation between the input and the output. For example, detail is a form of transformation that breaks up the input into two or more different types of distinguishing details. Another form of transformation is to duplicate by replacing the input. Transformation involves activities such as brainstorming, analysis, inference, drawings, etc. Visser defines evaluation as an activity that occurs once a design is presented as an "idea" for the solution. The design may or may not be presented to colleagues or fellow design team members for evaluation.

Representations constructed reveal a number of internal and external design activities and structures that lead to the proposal of different dimensions. Some examples of external design activities defined by Visser (2006) are the creation of

[2] For example Visser states that a lawyer would not be considered a designer, but a legal specialist who created news laws and legislation would be considered a designer. Also a doctor would not be considered a designer but medical personnel creating a new device to treat cancer would be considered a designer.

physical representations like “flowcharts, notes, drawings, plans, scale models, and graphics” (p. 128) [44]. Visser explains that often the creation of physical external representations allows the designer to complete analysis which is difficult or either entirely impossible on internal representations. According to Visser such activities facilitate design ideas and make it easier to manipulate them into possible components for a design solution. Her constructed representations are used for various purposes to influence the design task. For example, constructed representations are used during the design process for functions including tracking ideas, promoting understanding, branching from idea to idea, and communicating. The nature and detail of such representations with respect to design are described in the context of individual and collaborative design as well as in different stages of the design process. For example, Visser describes design as initial representations, external representations, required representations (design problems), intermediate representations, and specification representations (design solutions).

Her book highlights a gap in design research focusing on designers’ cognitive activities, which is the type of problem this dissertation is focused on solving. Her work is unique and pertinent to this dissertation because she actually translated her empirical data into a theoretical model of cognitive design activity that may be insightful for future design education.

Schön- Design as Reflection in Action

In reference to the history of design as a practice, Visser's work picked up where K. Dorst left off on his 1997 doctoral thesis and elaborated on certain points from both schools of thought in order to set up a foundation for her design theory

[103]. She references K. Dorst in her book but her book goes into more detail than the former did. She praises K. Dorst for his SIT inspired research which is presented in a clearer and more detailed fashion than Schön's work. In a prior publication Roozenburg et al. present a comparison of Schön's theory of reflection-in-action with Simon's view of design as rational problem solving [46]. Both views were used to construct a coding scheme (not detailed in their paper) and applied to the same set of design data for empirical comparison. Experienced designers were tasked with designing a litter disposal system for Dutch trains and given 2.5 hours to complete the task. The second author (K. Dorst) further investigated that Dutch train study and presented the work as partial requirements for his thesis. The goal of the Roozenburg et al. paper was to validate Schön's theory of reflection-in-action with what really happens during design. It was concluded that Schön's reflection-in-action theory does not clearly draw conclusions for the design process, as does Simon's rational problem solving. Hence an overall description of the design process from beginning to the end is not found in Schön's reflection-in-action. Roozenburg et al. (1998) did however crown Schön with the achievement of the "emancipation of design…a vindication of what practitioners really do" because he highlighted the extension of design as more than an application of scientific knowledge [46] (p. 29). Nevertheless, they do not hold that he (Schön) has many other contributions to the field of design and in particular that his theory in practice is "weak and fuzzy" (p. 29). Roozenburg et al. conclude that for practical purposes Schön's theory is elusive or entirely invisible. They do however claim that they may have been apprehensive in looking for practical

application of a work considered to be foundational and practically more removed from the bigger picture.

In their chapter Roozenburg et al. describe a basic dialogue with a problem Schön labeled the model of Technical Rationality.[3] Technical Rationality involves steps for applying basic scientific knowledge and skills to problem solving. A note is made that Schön does not agree with this bounded view of problem solving because it would only work for simple, well-structured problems. Schön's view of design problems are more ill structured and messy, which is why the model of Technical Rationality is limited. He views problems solving as naming and framing, which leads to technical problem solving. Schön views the practice of competent professionals not capable of fitting within the model of Technical Rationality. He sees design as a reconstruction (conversation) of the problem to understand it, which then reveals new ideas that require more reflective practice in design. During this conversation with the design problem the following steps are happening (a) naming, (b) framing, (c) making moves, and (d) evaluating the moves are all occurring. Roozenburg et al. state that Schön's framing views what designers do in practice as "hammering at an open door" which is an overstatement of the role of framing within design [46].

---

[3] This is described in his book The Reflective Practitioner 45. Schon, D., *The Reflective Practitioner: How Professionals Think in Action* 1983: Basic Books

From: University of Maryland IRB
To: Linda C. Schmidt; Sophoria Nicole Westmoreland
Subject: IRB Protocol Approval
Date: Wednesday, September 22, 2010 2:55:41 PM
Attachments: ATT00018.png

UNIVERSITY OF MARYLAND
INSTITUTIONAL REVIEW BOARD

Initial Application Approval

To:	Principal Investigator, Dr. Linda C. Schmidt, Mechanical Engineering Student, Sophoria Westmoreland, Mechanical Engineering
From:	James M. Hagberg IRB Co-Chair University of Maryland College Park
Re:	IRB Protocol: 10-0530 - Cognitive Design Tasks Study
Approval Date:	September 22, 2010
Expiration Date:	September 22, 2013
Application:	Initial
Review Path:	Exempt

The University of Maryland, College Park Institutional Review Board (IRB) Office approved your Initial IRB Application. This transaction was approved in accordance with the University's IRB policies and procedures and 45 CFR 46, the Federal Policy for the Protection of Human Subjects. Please reference the above-cited IRB Protocol number in any future communications with our office regarding this research.

Recruitment/Consent: For research requiring written informed consent, the IRB-approved and stamped informed consent document will be sent via mail. The IRB approval expiration date has been stamped on the informed consent document. Please note that research participants must sign a stamped version of the informed consent form and receive a copy.

Continuing Review: If you intend to continue to collect data from human subjects or to analyze private, identifiable data collected from human subjects, beyond the expiration date of this protocol, you must submit a Renewal Application to the IRB Office 45 days prior to the expiration date. If IRB Approval of your protocol expires, all human subject research activities including enrollment of new subjects, data collection and analysis of identifiable, private information must cease until the Renewal Application is approved. If work on the human subject portion of your project is complete and you wish to close the protocol, please submit a Closure Report to irb@umd.edu.

Modifications: Any changes to the approved protocol must be approved by the IRB before the change is implemented, except when a change is necessary to eliminate

Figure 57: IRB Approval Page 1

an apparent immediate hazard to the subjects. If you would like to modify an approved protocol, please submit an Addendum request to the IRB Office.

Unanticipated Problems Involving Risks: You must promptly report any unanticipated problems involving risks to subjects or others to the IRB Manager at 301-405-0678 or jsmith@umresearch.umd.edu

Additional Information: Please contact the IRB Office at 301-405-4212 if you have any IRB-related questions or concerns. Email: irb@umd.edu

The UMCP IRB is organized and operated according to guidelines of the United States Office for Human Research Protections and the United States Code of Federal Regulations and operates under Federal Wide Assurance No. FWA00005856.

0101 Lee Building
College Park, MD 20742-5125
TEL 301.405.4212
FAX 301.314.1475
irb@umd.edu
http://www.umresearch.umd.edu/IRB

Figure 58: IRB Approval Page 2

University of Maryland College Park
Department of Mechanical Engineering

Project Title *Cognitive Design Tasks Study - PROFESSIONAL*

Purpose of the Study *This research is being conducted by* ***Dr. Linda Schmidt*** *at the University of Maryland, College Park. We are inviting you to participate in this research project because you are or have been a professional engineering designer. The purpose of this research project is to gain insight into the mechanical engineering design process by examining journals created by professional designers.*

Procedures *The procedures involve interviewing you about the journal usage and projects you have done. Any journaling that you have done of a non-proprietary nature that we could scan and use for research purposes.*

Potential Risks and Discomforts *There are no risks for participating in this study.*

Potential Benefits *The benefits to you include improved understanding during the design process. We hope that, in the future, other people might benefit from this study through improved understanding of the cognitive aspects of the design process.*

Confidentiality *Any potential loss of confidentiality will be minimized by keeping the scanned digital documents released by you in a safe place and using them only for the purposes of this research. If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.* ***By signing this agreement you give permission to the investigators to use your sketches, phrases, comments, examples written in your journal in published documents.***

Right to Withdraw and Questions *Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify. If you decide to stop taking part in the study, if you have questions, concerns, or complaints, or if you need to report an injury related to the research, please contact the investigator, Dr. Linda Schmidt at 301-405-4518.*

Participant Rights *If you have questions about your rights as a research participant or wish to report a research-related injury, please contact:* **University of Maryland College Park, Institutional Review Board Office, 0101 Lee Building, College Park, Maryland, 20742, E-mail: irb@umd.edu, Telephone: 301-405-0678** *This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.*

Statement of Consent *Your signature indicates that you are at least 18 years of age; you have read this consent form or have had it read to you; your questions have been answered to your satisfaction and you voluntarily agree to participate in this research study. You will receive a copy of this signed consent form. If you agree to participate, please sign your name below.*

Signature and Date	**NAME OF SUBJECT [Please Print]**	
	SIGNATURE OF SUBJECT	
	DATE	

Figure 59: Professional Designer Consent Form

University of Maryland College Park
Department of Mechanical Engineering

Project Title *Cognitive Design Tasks Study - STUDENT*

Purpose of the Study *This research is being conducted by* ***Dr. Linda Schmidt*** *at the University of Maryland, College Park. We are inviting you to participate in this research project because you are a student in University of Maryland in an advanced design course. The purpose of this research project is to gain insight into the mechanical engineering design process by examining journals created by students in design courses.*

Procedures *The procedures involve using the design journal to record during the mechanical engineering design process according to the* ***Design Journal Guidelines****. The investigators will periodically scan your journal pages and collect the journal at the end of the course or your participation in the study.*

Potential Risks and Discomforts *There are no risks for participating in this study.*

Potential Benefits *The benefits to you include improved understanding during the design process. We hope that, in the future, other people might benefit from this study through improved understanding of the cognitive aspects of the design process.*

Confidentiality *Any potential loss of confidentiality will be minimized by keeping the journals in a safe place and using them only for the purposes of this research. Any scanned digital documents will be kept on the investigators computer. If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.* ***By signing this agreement you give permission to the investigators to use your sketches, phrases, comments, examples written in your journal in publications.***

Right to Withdraw and Questions *Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify. If you decide to stop taking part in the study, if you have questions, concerns, or complaints, or if you need to report an injury related to the research, please contact the investigator, Dr. Linda Schmidt at 301-405-4518.* **Your decision to participate will have no impact on your grades for this course.**

Participant Rights
If you have questions about your rights as a research participant or wish to report a research-related injury, please contact: **University of Maryland College Park, Institutional Review Board Office, 0101 Lee Building, College Park, Maryland, 20742, E-mail: irb@umd.edu, Telephone: 301-405-0678** *This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.*

Statement of Consent
Your signature indicates that you are at least 18 years of age; you have read this consent form or have had it read to you; your questions have been answered to your satisfaction and you voluntarily agree to participate in this research study. You will receive a copy of this signed consent form. If you agree to participate, please sign your name below.

Signature and Date	**NAME OF SUBJECT [Please Print]**	
	SIGNATURE OF SUBJECT	
	DATE	

Figure 60: Student Consent Form

Design Journal Guidelines

ENME 472 Integrated Product and Process Development

Pilot Study- This is a preliminary study on students using design journals as a part of the mechanical engineering design process. This pilot study is for students in ENME 472 design course at [redacted]

NOTEBOOK INTRODUCTION

Engineering notebooks are an important part of the design process. Leonardo Da Vinci used notebooks to record his inventions. Many documented benefits exist for the user such as:

- Writing helps students learn
- Gain a deeper understanding
- Enhance cognitive abilities inside and outside of the classroom or lab
- Better for practicing design

EXPECTATIONS

In order to participate in these study students must be registered in ENME 472 for fall 2010 semester. Students participating in this study will be required to use the design journal during lab meetings and also outside during team meetings. This study is designed to incorporate the design journal into the normal activities that a 472 student would already be participating in. This study just provides a medium to record that process.

TIME

Students who agree will participate in the study for 4-6 weeks. The study will begin the 2nd week of the fall 2010 semester.

RECORDING INFORMATION

1. A design journal is a permanent record of what happened during the design process, i.e. the development of your design.
   - the ideas of its author
   - the alternatives considered
   - decisions reached
   - interactions with other people and with organizations
   - the changes made along the way
   - the implementation flow of projects, labs, etc.
2. All letters, sketches, photos, charts or computer printouts pertinent to the project should be permanently put in the notebook with your initials and date. (use tape to secure)
3. Don't erase. Cross out errors and make a new entry. Entries should not be changed at a later date. Make a new entry, pointing out any change.
4. Notations should be made of the progress and completion of compounds, assemblies or models which are being prepared for testing. These entries should make clear, as by reference to a previous sketch, as to how the compound or equipment is being made.
5. Don't leave blank areas on a page.
6. Never, under any circumstance, should you remove a page.
7. Include detailed notes on all discussions and thoughts on your goals.

REFLECTIVE QUESTIONS

The following questions are meant to stimulate after a team meeting, brainstorming session, analysis, design, or internet searches.

-What decisions were made during this session?
-What role did you contribute to the lab session today?
-How do you feel about the progress your team is making this week?
-What concepts or new ideas for the project do you have?
-What was new and surprising to you today?
-What ideas did you come up with today?
-What questions are left unanswered?
-What are your next action items?

EXIT INTERVIEWS

At the conclusion of this study you will be asked to participate in a short exit interview on the effectiveness of the implementation of the design journals in engineering courses.

COMPENSATION

The satisfactory completion of the journal is a course requirement worth 5% of your total grade. The journal pages will be scanned periodically and you will be given feedback as to their adequacy.

QUESTIONS

This study is being managed by [redacted] *(472 Teaching Assistant) under the supervision of her advisor* [redacted] *in the Department of Mechanical Engineering.* [redacted]

Figure 61: Team Study Design Journal Guidelines

Design Journal Guidelines

ENME 472 Integrated Product and Process Development

Pilot Study- This is a preliminary study on students using design journals as a part of the mechanical engineering design process. This pilot study is for students in ENME 472 design course at [redacted]*.*

NOTEBOOK INTRODUCTION

Engineering notebooks are an important part of the design process. Leonardo Da Vinci used notebooks to record his inventions. Many documented benefits exist for the user such as:

- Writing helps students learn
- Gain a deeper understanding
- Enhance cognitive abilities inside and outside of the classroom or lab
- Better for practicing design

EXPECTATIONS

In order to participate in these study students must be registered in ENME 472 for fall 2010 semester. Students participating in this study will be required to use the design journal during lab meetings and also outside during team meetings. This study is designed to incorporate the design journal into the normal activities that a 472 student would already be participating in. This study just provides a medium to record that process.

TIME

Students who agree will participate in the study for 4-6 weeks. The study will begin the 2nd week of the fall 2010 semester.

RECORDING INFORMATION

1. A design journal is a permanent record of what happened during the design process, i.e. the development of your design.

- the ideas of its author
- the alternatives considered
- decisions reached
- interactions with other people and with organizations
- the changes made along the way
- the implementation flow of projects, labs, etc.

2. All letters, sketches, photos, charts or computer printouts pertinent to the project should be permanently put in the notebook with your initials and date. (use tape to secure)
3. Don't erase. Cross out errors and make a new entry. Entries should not be changed at a later date. Make a new entry, pointing out any change.
4. Notations should be made of the progress and completion of compounds, assemblies or models which are being prepared for testing. These entries should make clear, as by reference to a previous sketch, as to how the compound or equipment is being made.
5. Don't leave blank areas on a page.
6. Never, under any circumstance, should you remove a page.
7. Include detailed notes on all discussions and thoughts on your goals.

REFLECTIVE QUESTIONS

The following questions are meant to stimulate after a team meeting, brainstorming session, analysis, design, or internet searches.

-What decisions were made during this session?
-What role did you contribute to the lab session today?
-How do you feel about the progress your team is making this week?
-What concepts or new ideas for the project do you have?
-What was new and surprising to you today?
-What ideas did you come up with today?
-What questions are left unanswered?
-What are your next action items?

EXIT INTERVIEWS

At the conclusion of this study you will be asked to participate in a short exit interview on the effectiveness of the implementation of the design journals in engineering courses.

COMPENSATION

Students who successfully complete the study will be provided with a gift card to a local establishment, i.e. the campus bookstore.

QUESTIONS

This study is being managed by [redacted] *(472 Teaching Assistant) under the supervision of her advisor* [redacted] *in the Department of Mechanical Engineering.* [redacted]

Figure 62: Individual Study Design Journal Guidelines

Design Journal Guidelines

ENME 472 Integrated Product and Process Development

Pilot Study- This is a study on students using design journals as a part of the mechanical engineering design process. This pilot study is for students in ENME 472 design course at The University of Maryland.

NOTEBOOK INTRODUCTION

Engineering notebooks are an important part of the design process. Leonardo Da Vinci used notebooks to record his inventions. Many documented benefits exist for the user such as:

- Writing helps students learn
- Gain a deeper understanding
- Enhance cognitive abilities inside and outside of the classroom or lab
- Better for practicing design

EXPECTATIONS

In order to participate in these study students must be registered in ENME 472 for Spring 2011 semester. Students participating in this study will be required to use the design journal during lab meetings and also outside during team meetings. This study is designed to incorporate the design journal into the normal activities that a 472 student would already be participating in. This study just provides a medium to record that process.

TIME

Students who agree will participate in the study for 5 weeks. The study will begin on **March 8, 2011** and end on **April 8, 2011.**

RECORDING INFORMATION

1. A design journal is a permanent record of what happened during the design process, i.e. the development of your design.
   - the ideas of its author
   - the alternatives considered
   - decisions reached
   - interactions with other people and with organizations
   - the changes made along the way
   - the implementation flow of projects, labs, etc.
2. All letters, sketches, photos, charts or computer printouts pertinent to the project should be permanently written into the notebook with your initials and date.
3. Don't erase. Cross out errors and make a new entry. Entries should not be changed at a later date. Make a new entry, pointing out any change.
4. Notations should be made of the progress and completion of compounds, assemblies or models which are being prepared for testing. These entries should make clear, as by reference to a previous sketch, as to how the compound or equipment is being made.
5. Don't leave blank areas on a page.
6. Never, under any circumstance, should you remove a page.
7. Include detailed notes on all discussions and thoughts on your goals.

REFLECTIVE QUESTIONS

The following questions are meant to stimulate after a team meeting, brainstorming session, analysis, design, or internet searches.

-What decisions were made during this session?
-What role did you contribute to the lab session today?
-How do you feel about the progress your team is making this week?
-What concepts or new ideas for the project do you have?
-What was new and surprising to you today?
-What ideas did you come up with today?
-What questions are left unanswered?
-What are your next action items?

EXIT INTERVIEWS

At the conclusion of this study you will be asked to participate in a short exit interview on the effectiveness of the implementation of the design journals in engineering courses.

COMPENSATION

Students who *successfully* complete the study will be provided with a $30 gift card to a local establishment, i.e. the campus bookstore.

QUESTIONS

This study is being managed by Sophoria "Nikki" Westmoreland (472 Teaching Assistant) under the supervision of her advisor Dr. Linda C. Schmidt in the Department of Mechanical Engineering. Nikki can be reached at snwest@umd.edu or at 301-405-4518 in her office.

Figure 63: Spring 2011 Design Journal Guidelines

427 DESIGN STUDY- SPRING 2011

March 15, 2011

The below signed student agrees to the loan of **1 pulse smartpen** for use in the 472 design study from **March 15, 2011 until April 15, 2011** and will return the complete contents of the box at the completion of this study on or before April 15, 2011.

The students will also write only in the smartpen journal and agree to upload and share the contents with the course instructor and TA during the design study using the online resources provided by the manufacturer of the smartpen.

The box includes:

1. Pulse smartpen
2. Headset
3. Notebook
4. USB mobile charging cradle
5. Protective soft case
6. 2 ink cartridges

____

Student Participant Sign AND Date

____

TA- Sophoria Westmoreland Sign AND Date

____

Professor- Dr. Linda Schmidt Sign AND Date

Created by: SNW March 15, 2011

Figure 64: Smart Pen Agreement Form

Design Journal Guidelines

ENME 472 Integrated Product and Process Development

This is a study with students using design journals as a part of the mechanical engineering design process. This study is for students in the ENME 472 senior capstone design course at The University of Maryland.

NOTEBOOK INTRODUCTION

Engineering notebooks are an important part of the design process. Leonardo Da Vinci used notebooks to record his inventions. Many documented benefits exist for the user such as:

- Writing helps students learn
- Gain a deeper understanding
- Enhance cognitive abilities inside and outside of the classroom or lab
- Better for practicing design

EXPECTATIONS

In order to participate in these study students must be registered in ENME 472. Students participating in this study will be required to use the design journal during lab meetings and also outside during team meetings. This study is designed to incorporate the design journal into the normal activities that a 472 student would already be participating in. This study just provides a medium to record that process.

The design journals will be checked weekly by Nikki and signed to monitor student participation. This is to ensure that the students are actually using the journals and not waiting until the end of the semester to make entries.

STUDY DURATION

Students will participate for the entire semester. (15 weeks) The study will begin the 1st week of the fall 2011 semester.

RECORDING IN THE JOURNAL

A design journal is a permanent record of what happened during the design process, i.e. the development of the design.

- the ideas of its author
- all alternative designs considered
- decisions reached by the author and the design team
- interactions with other people and with organizations
- changes made along the way to the design
- implementation flow of projects, labs, etc.

1. All letters, sketches, photos, charts or computer printouts pertinent to the design project should be permanently put in the design journal with your initials and date. (use tape to secure)
2. Don't erase. Cross out errors and make a new entry. Entries should not be changed at a later date. Make a new entry, pointing out any change.
3. Notations should be made of the progress and completion of compounds, assemblies or models which are being prepared for testing. These entries should make clear, as by reference to a previous sketch, as to how the compound or equipment is being made.
4. Don't leave blank areas on a page. If needed simply draw a line through across that page.
5. Never, under any circumstance, should you remove a page. Also it is best if pages are not skipped in the design journal.
6. Include detailed notes on all discussions and thoughts on your goals for the design project.

SUGGESTED REFLECTIVE QUESTIONS

The following questions are meant to stimulate after a team meeting, brainstorming session, analysis, design, or internet searches.

-What decisions were made during this session?
-What role did you contribute to the lab session today?
-How do you feel about the progress your team is making this week?
-What concepts or new ideas for the project do you have?
-What was new and surprising to you today?
-What ideas did you come up with today?
-What questions are left unanswered?
-What are your next action items?

PARTICIPANT COMPENSATION

Students who consistently record in the design journals will be compensated every 5 weeks with a $20 Gift Card to Barnes and Noble that will be delivered electronically to their e-mail address.

EXIT INTERVIEW

At the conclusion of this study you will be asked to participate in a short exit survey on the effectiveness of the implementation of the design journals in engineering courses.

QUESTIONS

This study is being managed by Sophoria "Nikki" Westmoreland (472 Teaching Assistant) under the supervision of her advisor Dr. Linda C. Schmidt in the Department of Mechanical Engineering. Nikki can be reached at snwest@umd.edu or at 301-405-4518 in her office. This study has been properly approved by the University of Maryland IRB.

Figure 65 : Fall 2011 Design Journal Guidelines

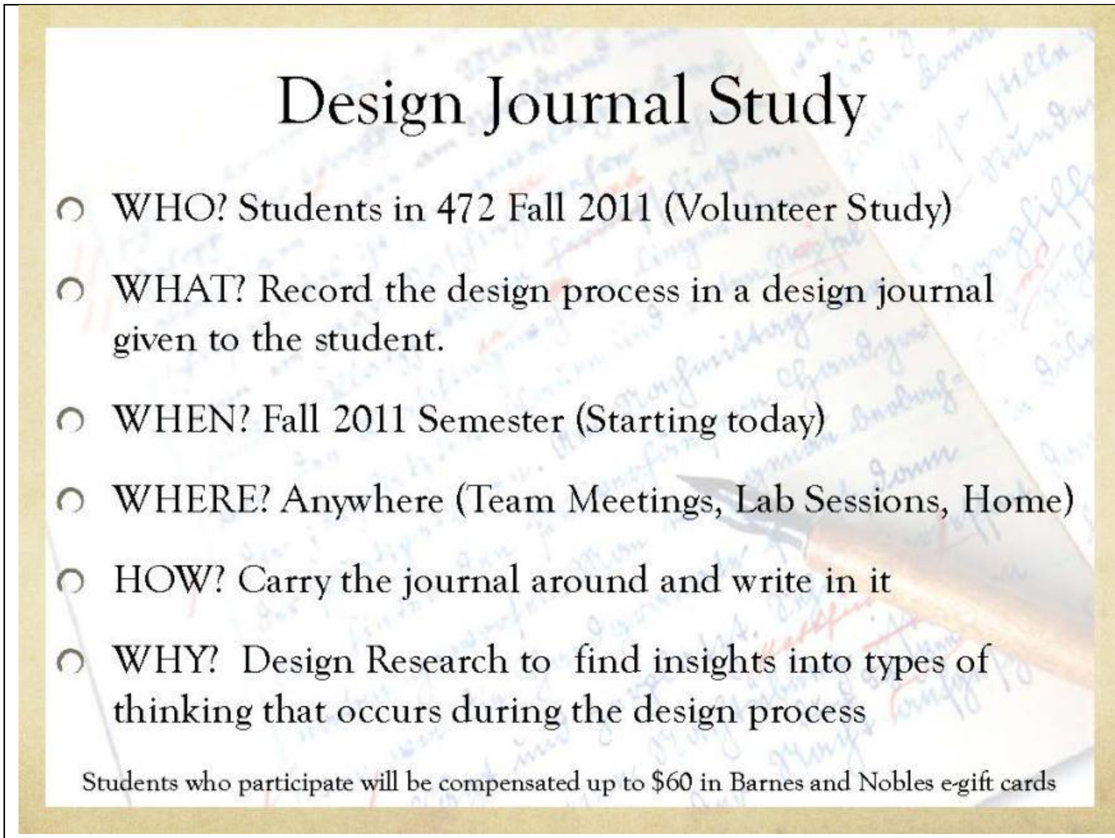


Figure 66: Design Study Intro Slide 1

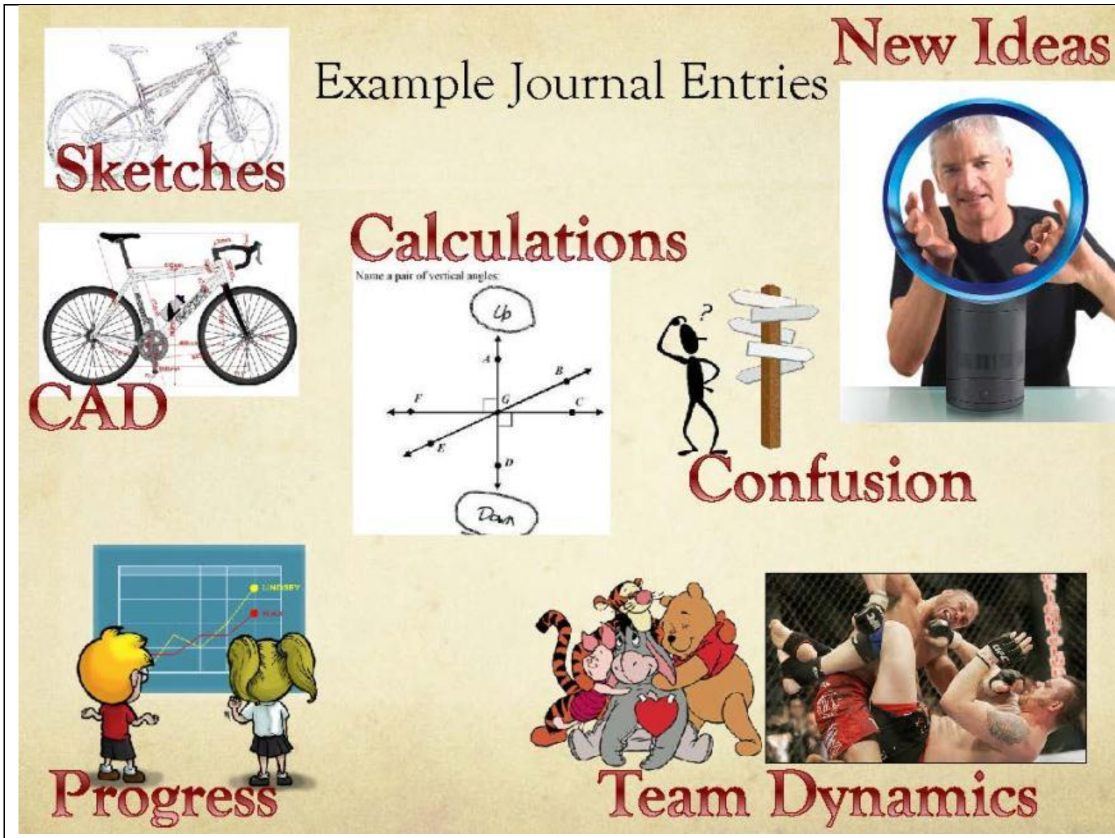


Figure 67: Design Study Intro Slide 2

DESIGN STUDY EXIT INTERVIEW

This interview is being recorded and all responses will be used for the purposes of this research project and kept confidential. ***All responses are confidential.*** *Please answer all questions to the best of your ability.*

STUDENT:
PROJECT:
INSTRUCTOR:
SECTION:
SEMESTER:
TIME in STUDY:

GENERAL

1. Did you ever make design notes during a previous design process? (*Topic-Connections AND Positive Impacts*)
2. When did you fill out the journal? (*Topic-Effectiveness of DJ during the Design Process*)
3. How often did you go back and read what you wrote? Did you add more notes or notations when you went back? (*Topic-Connections AND Positive Impacts*)
4. Do you think it added time to your design work? (*Topic-Improvements in the Design Process*)
5. Do you normally sketch? Did you sketch more with the design journals? (*Topic-Sketching During the Design Process*)
6. Did you write more than you have in previous design courses? (*Topic-Improved Thought Process*)
7. Did it feel awkward to use the design journal? (*Topic-Negative Impacts*)
8. Do you think design journals should be a course requirement in design courses? (*Topic-Recommendations*)
9. Before participating in this study, what was your idea of a design journal? (*Topic-Understanding*)
10. Were the instructions clear enough for this study? (*Topic-Journal Layout Questions*)
11. Will you write design notes again during a future design process? (*Topic-Connections AND Positive Impacts*)

STUDENT SPECIFIC

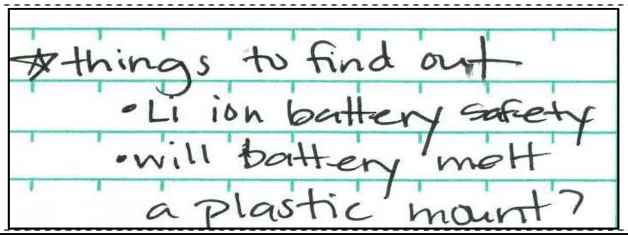
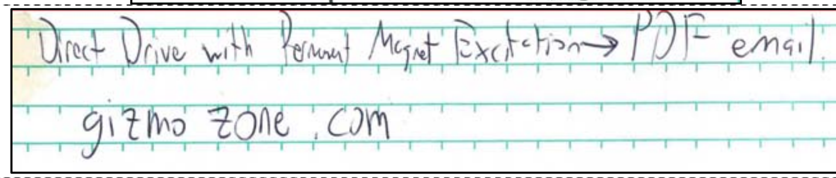
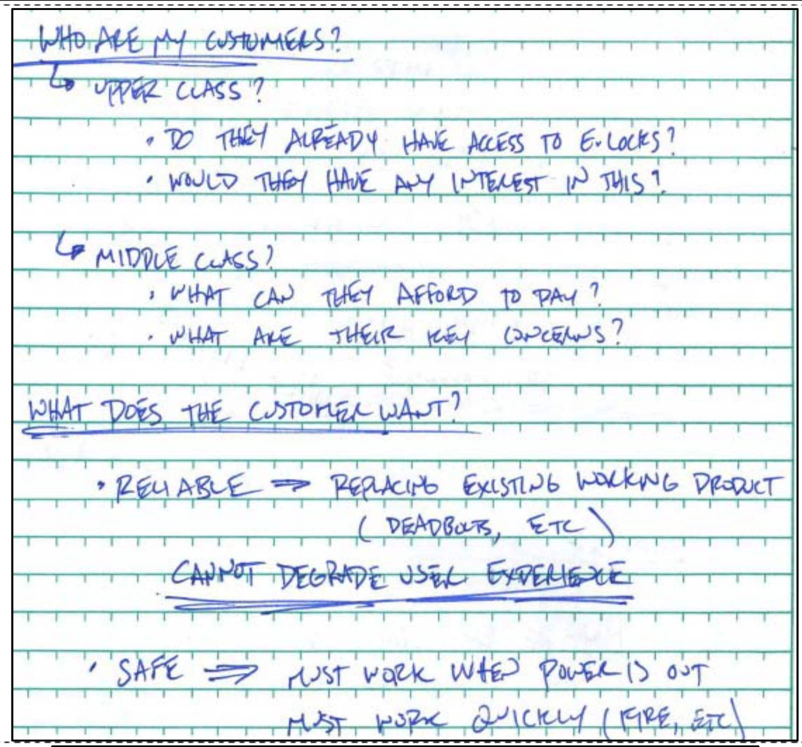
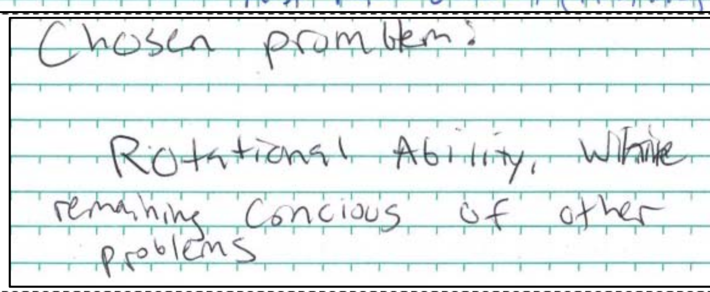
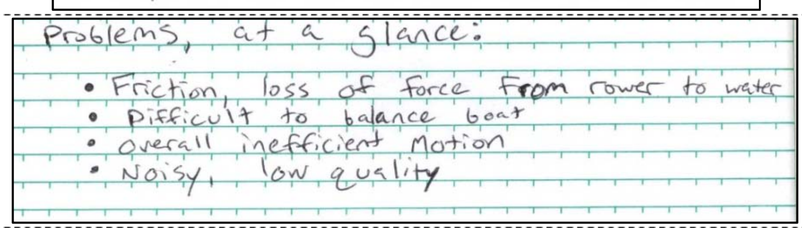
1. Question 1
2. Question 2
3. Question 3

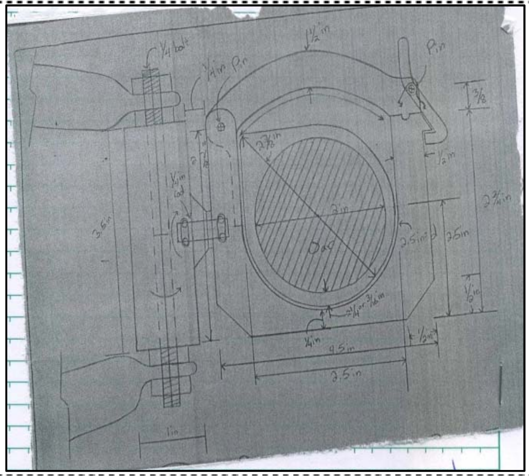
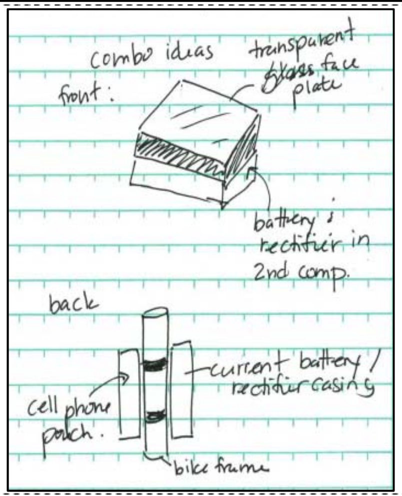
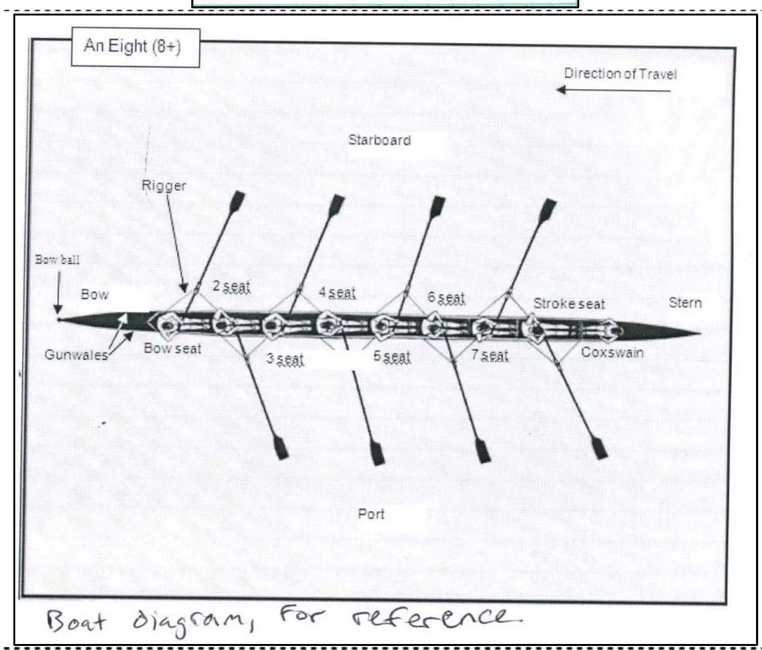
Thank You for Your Participation

11/8/2010 8:53 AM Page 1

Figure 68: Student Design Study Exit Interview Form

Table 83: Cognitive Code Journal Examples

Search (1)	 ☆ things to find out • Li ion battery safety • will battery melt a plastic mount?
	 Direct Drive with Permanent Magnet Excitation → PDF email gizmo zone .com
Customer Requirements (2)	 WHO ARE MY CUSTOMERS? ↳ UPPER CLASS? • DO THEY ALREADY HAVE ACCESS TO E-LOCKS? • WOULD THEY HAVE ANY INTEREST IN THIS? ↳ MIDDLE CLASS? • WHAT CAN THEY AFFORD TO PAY? • WHAT ARE THEIR KEY CONCERNS? WHAT DOES THE CUSTOMER WANT? • RELIABLE ⇒ REPLACING EXISTING WORKING PRODUCT (DEADBOLTS, ETC) CANNOT DEGRADE USER EXPERIENCE • SAFE ⇒ MUST WORK WHEN POWER IS OUT MUST WORK QUICKLY (FIRE, ETC)
Problem Statement Clarification (3)	 Chosen promblem: Rotational Ability, while remaining concious of other problems
	 Problems, at a glance: • Friction, loss of force from rower to water • Difficult to balance boat • overall inefficient motion • Noisy, low quality

<table>
<tr><td>Project Ideas (4)</td><td>
</td></tr>
<tr><td></td><td>
</td></tr>
<tr><td>References (5)</td><td>
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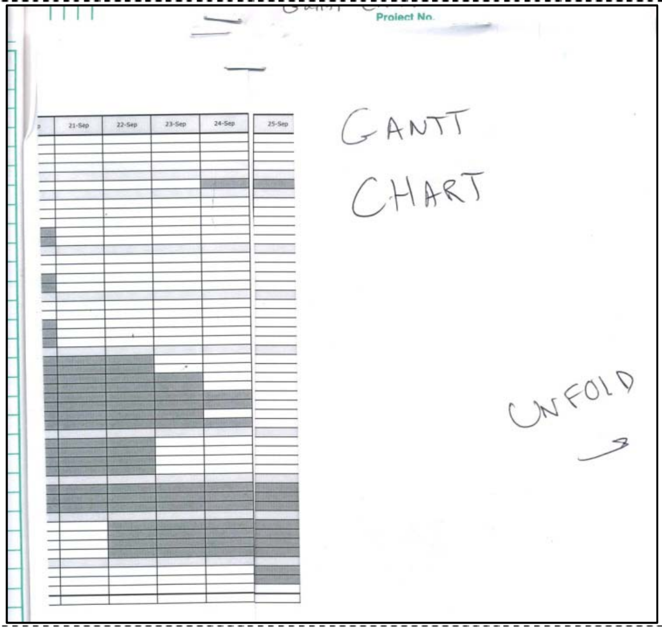
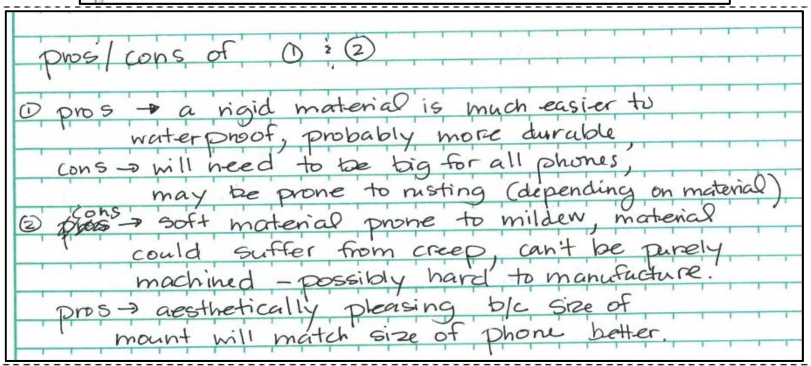


Material Options (6)



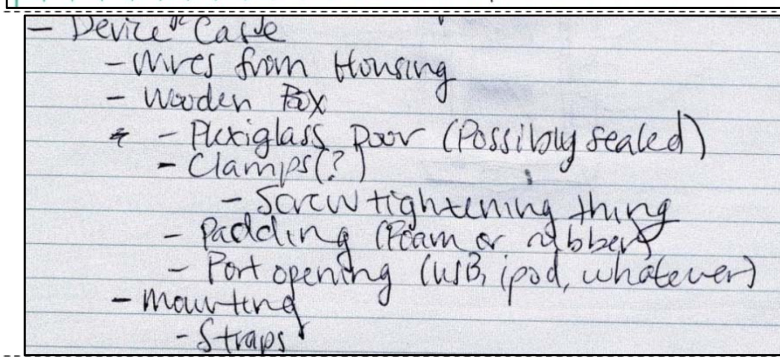
pros/cons of ① & ②

① pros → a rigid material is much easier to waterproof, probably more durable,

cons → will need to be big for all phones, may be prone to rusting (depending on material)

② ~~pros~~ cons → soft material prone to mildew, material could suffer from creep, can't be purely machined – possibly hard to manufacture.

pros → aesthetically pleasing b/c size of mount will match size of phone better.

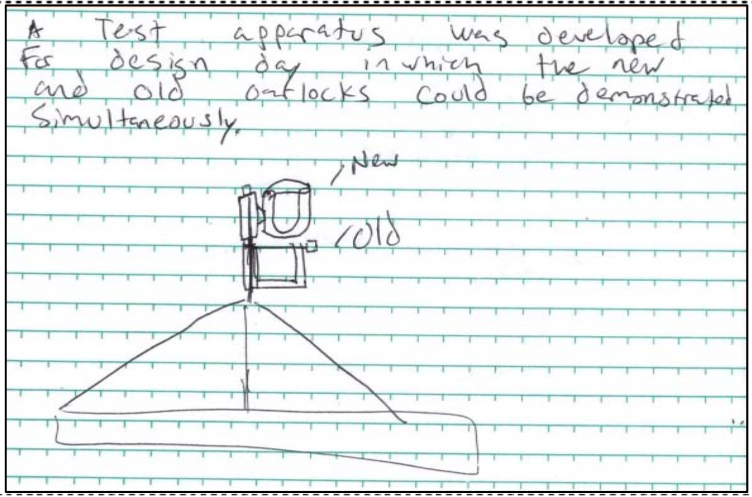


- Device Case
  - Wires from Housing
  - Wooden Box
  - Plexiglass Door (Possibly sealed)
    - Clamps(?)
      - Screw tightening thing
    - Padding (Foam or rubber)
    - Port opening (USB, ipod, whatever)
  - Mounting
    - Straps

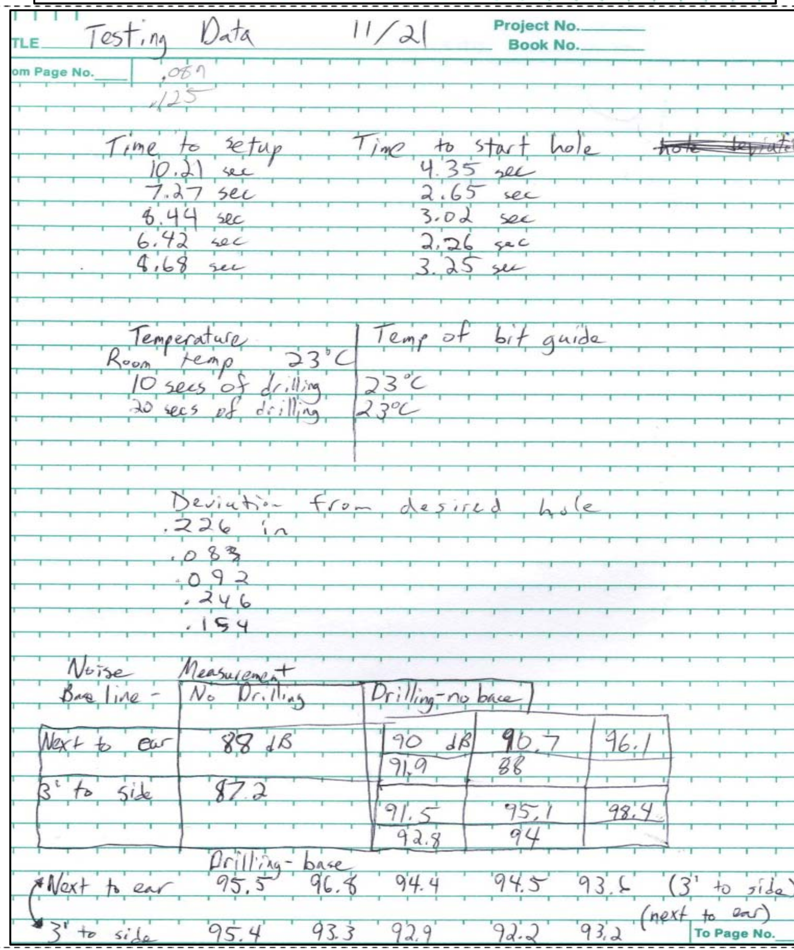
Estimates (7)	Compressed $V_0 = \frac{Qd_0}{k\varepsilon_0 A}$ Released $V = \frac{Q(d_0+a)}{k\varepsilon_0 A}$ $a \approx 20\% d$ $V_1 - V_0 = \frac{Q}{k\varepsilon_0 A}(a)$ $a = b = 50mm \approx .05m$ $d = 2mm \approx 0.002m$ $E \approx 1.4 MPa$ $k = \frac{EA}{L}$ $k = \frac{1.4\times10^6(.05^2)}{.002}$ $k = 1.75\times10^6$ N/m $F = kx = ka = 700N$ $a \approx 0.002(.2) =$
	Energy Harvesting from human footsteps • Body emits 100 W energy at rest • Current shoe generators can achieve 3-6 Watts power output • Gym equipment used to charge generators Efficiency of Piezoelectricity vs. Fluid Movement "Crowd Farming": Piezoelectric generators in high population areas 1 Footstep = Power for 2 60W lightbulbs for 1 second 94,162,203 footsteps could launch a space shuttle • Problem: Finding how much energy should be harvested from a person Energy = Mass · Gravity · Displacement (Joules) $75Kg \cdot 9.81 m/s^2 \cdot 0.01m = 7.35$ Joules of energy $Power = \frac{Energy}{Time} = \frac{7.35J}{1s} = 7.35W$
Analogical Reasoning (8)	From Page No.____ Additionally, the tradeoff mentioned earlier between clamp strength and heat transfer could prove a difficult obstacle to overcome. ~~Normally~~ users have to only concentrate on heat being generated at the drill bit location. Designers ~~to~~ do not want users to have to concentrate on normal heat generation ~~within the motor,~~ at the drill bit and

Assumptions (9)	MEDIAN INCOME (MIDDLE CLASS) DC – 80K MD – 87K VA – 73K } \$60,000 PER FAMILY
Calculations (10)	$VT^n = C$ $VT_0^n = V((1-.3))T_f^n$ $\frac{V T_0^n}{V(.7)^{1/.3}} = T_f^n$ $\frac{T_0}{(.7)^{1/.3}} = T_f$ $3.28\, T_0 = T_f$ $\frac{3.28-1}{1} = 2.28 \times 100\%$ 228%
	$E = \frac{\sigma}{\varepsilon}$ $\varepsilon = K\varepsilon_0$ $V = \frac{Fd}{q} = Ed$ $C = \frac{A\varepsilon}{d}$
Questioning (11)	CONSIDER: how and where will the measurements be seen?
	★ are we willing to sacrifice GPS use as a means for combining mount locations? ★ would it be too much to mount battery & rectifier with phone on handlebars? → then rear-wheel dynamo wire routing becomes an increased challenge BUT reduces overall # of wires. & setup time.

Testing Procedures (12)



A Test apparatus was developed for design day in which the new and old outlocks could be demonstrated Simultaneously.



TITLE Testing Data 11/21

Project No.

Book No.

From Page No.

.087

.125

Time to setup	Time to start hole
10.21 sec	4.35 sec
7.27 sec	2.65 sec
8.44 sec	3.02 sec
6.42 sec	2.26 sec
4.68 sec	3.25 sec

Temperature	Temp of bit guide
Room temp 23°C	
10 secs of drilling	23°C
20 secs of drilling	23°C

Deviation from desired hole

.226 in

.083

.092

.246

.154

Noise Measurement

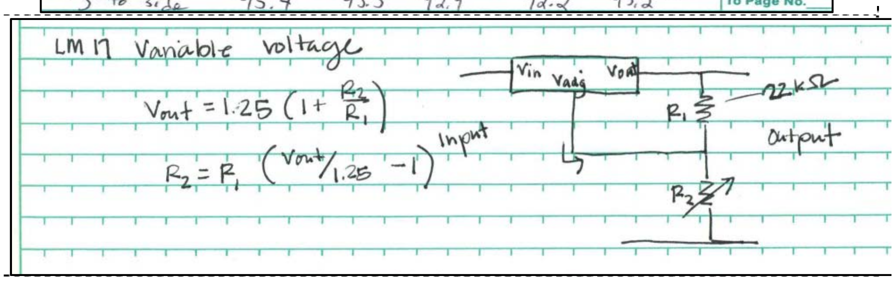
Base line -	No Drilling	Drilling - no base		
Next to ear	88 dB	90 dB / 91.9	96.7 / 88	96.1
3' to side	87.2	91.5 / 92.8	95.1 / 94	98.4

Drilling - base

Next to ear	95.5	96.8	94.4	94.5	93.6	(3' to side)
3' to side	95.4	93.3	92.9	92.2	93.2	(next to ear)

To Page No.

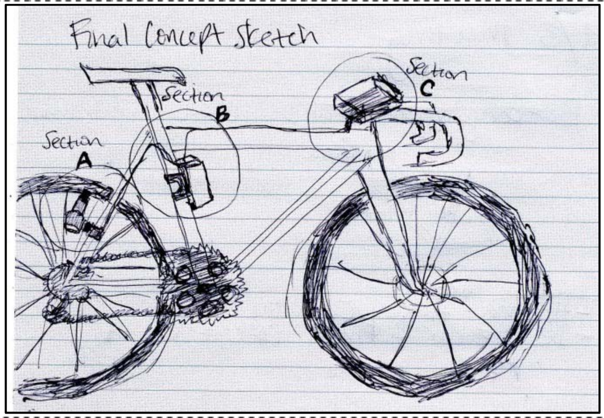
Variables (13)



LM 17 Variable voltage

$$V_{out} = 1.25\left(1 + \frac{R_2}{R_1}\right)$$

$$R_2 = R_1\left(V_{out}/1.25 - 1\right)$$

<table>
<tr><td>Recommendations (14)</td><td></td></tr>
<tr><td>Conclusions(15)</td><td>
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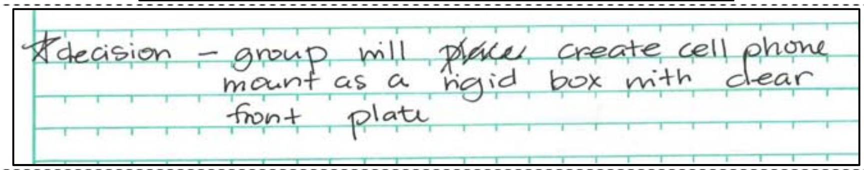
<tr><td></td><td>
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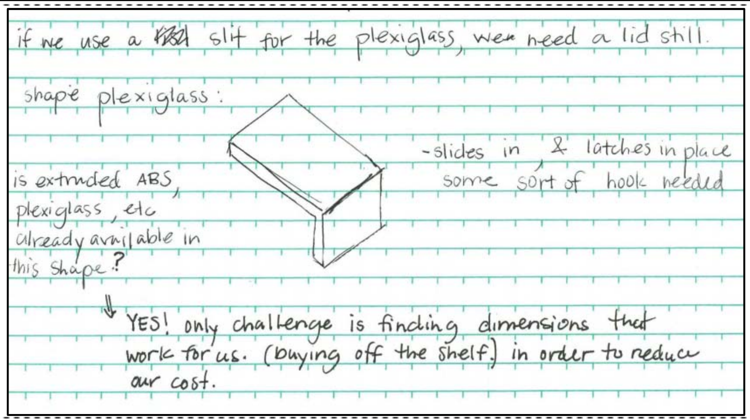
<tr><td>Explanations (16)</td><td>
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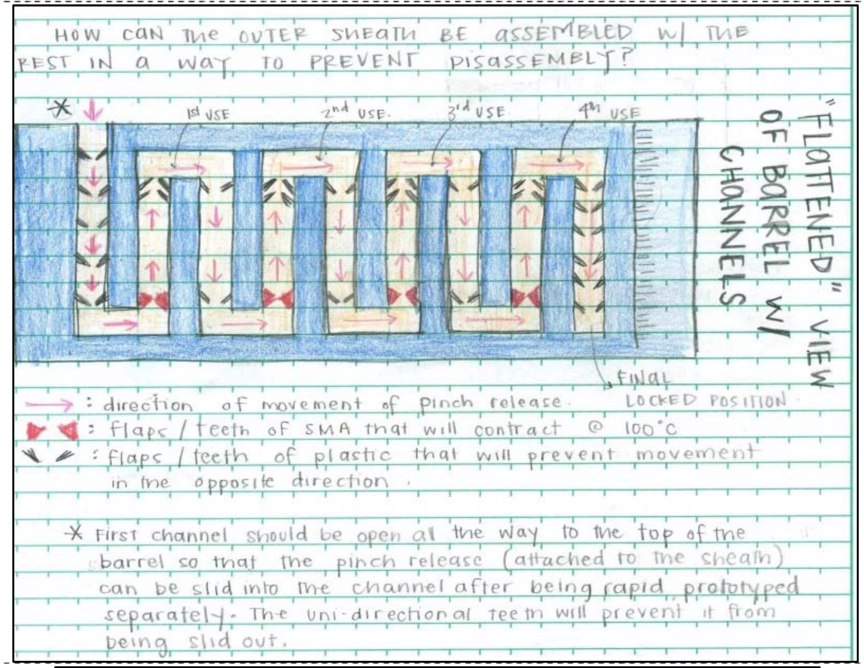
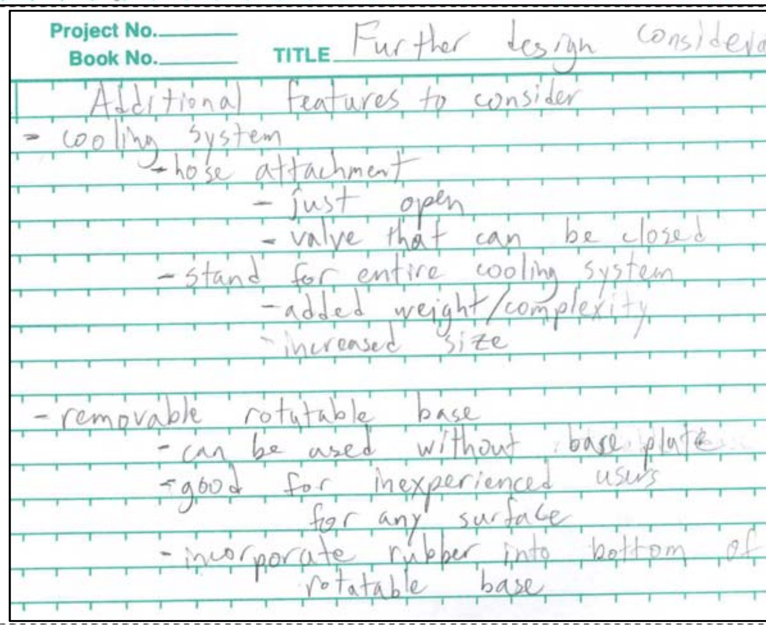
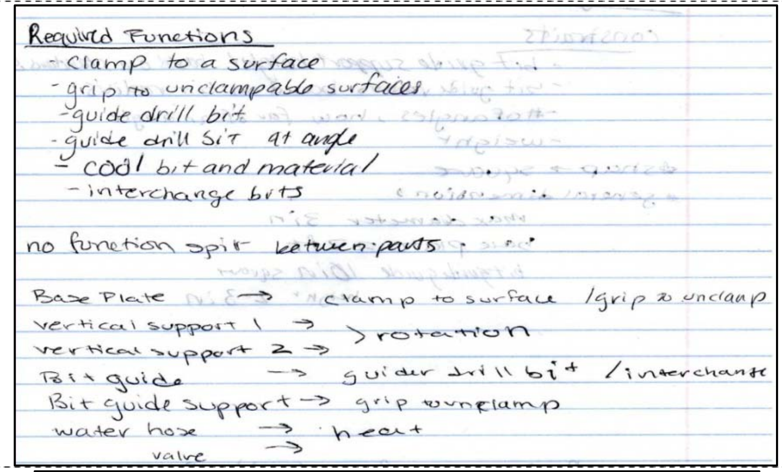


Criteria List (17)


Project No.
Book No.
TITLE Further design considera

Additional features to consider
- cooling system
  - hose attachment
    - just open
    - valve that can be closed
  - stand for entire cooling system
    - added weight/complexity
    - increased size

- removable rotatable base
  - can be used without base plate
  - good for inexperienced users
    for any surface
  - incorporate rubber into bottom of
    rotatable base

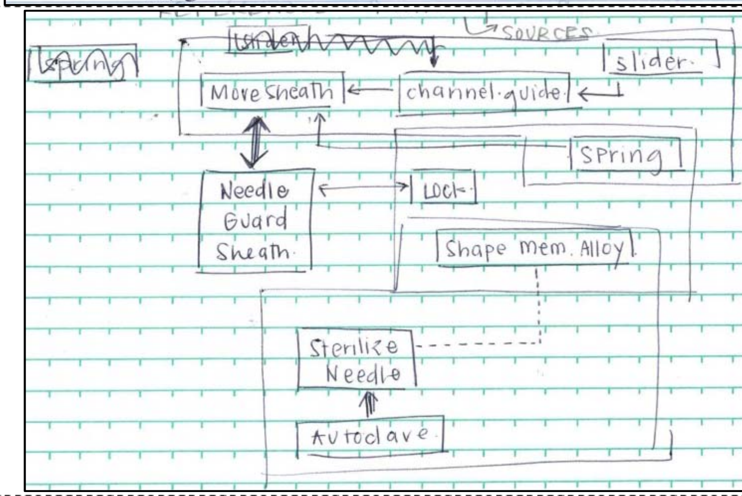


Required Functions
- clamp to a surface
- grip to unclampable surfaces
- guide drill bit
- guide drill bit at angle
- cool bit and material
- interchange bits

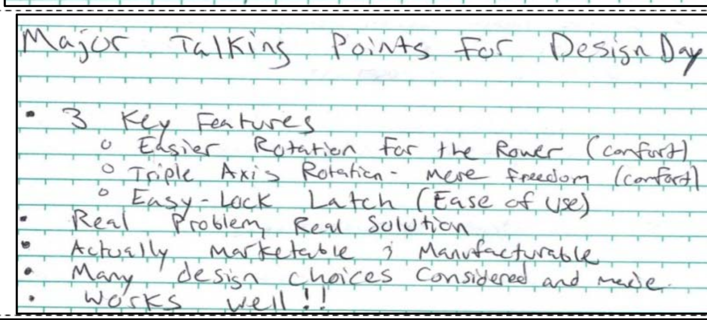
no function split between parts

Base Plate → clamp to surface / grip to unclamp
vertical support 1 → } rotation
vertical support 2 →
Bit guide → guider drill bit / interchange
Bit guide support → grip to unclamp
water hose → heat
valve →

Design Changes (18)

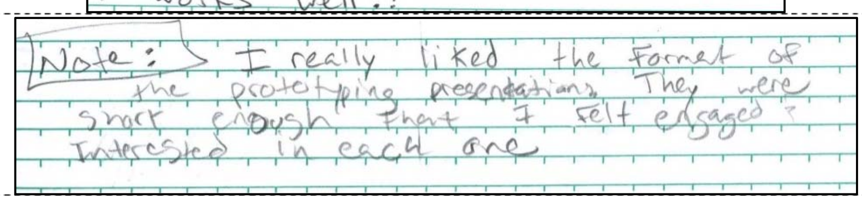


Personal Notes (19)



Major Talking Points for Design Day

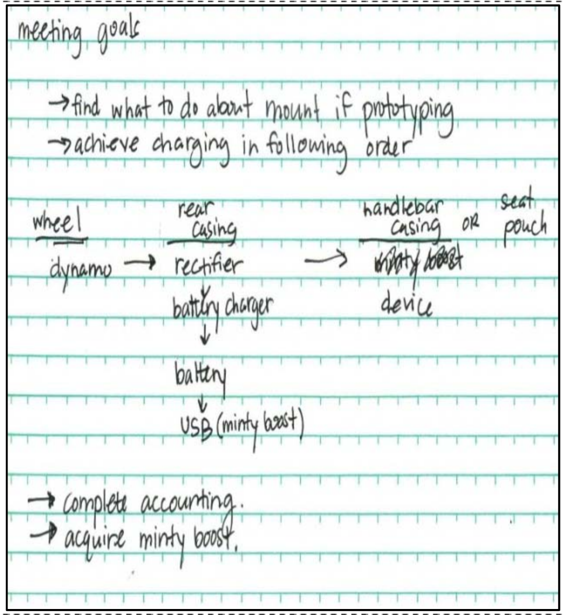
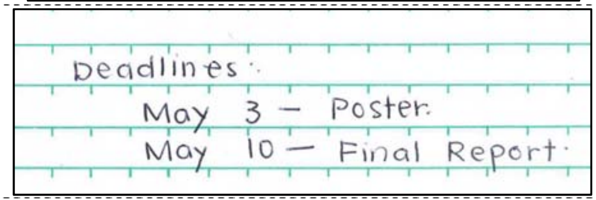
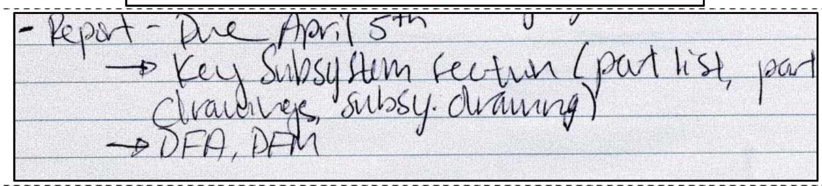
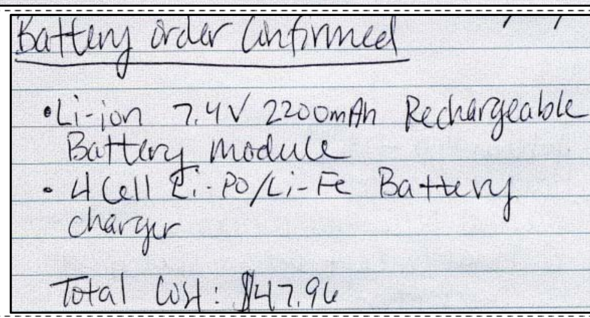
- 3 Key Features
  - Easier Rotation for the Rower (comfort)
  - Triple Axis Rotation - more freedom (comfort)
  - Easy-Lock Latch (Ease of Use)
- Real Problem, Real Solution
- Actually Marketable & Manufacturable
- Many design choices considered and made
- Works well!!

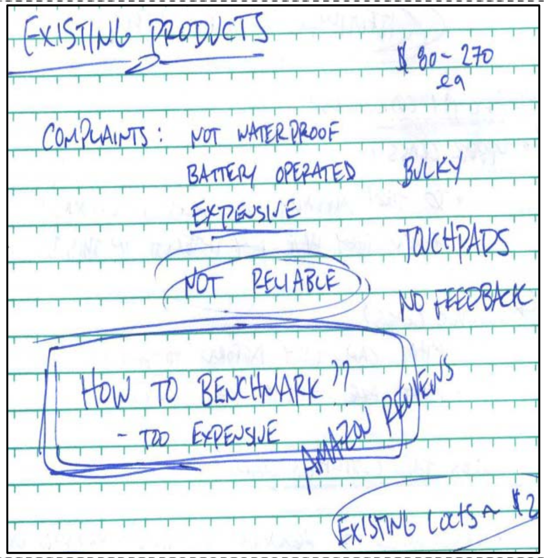
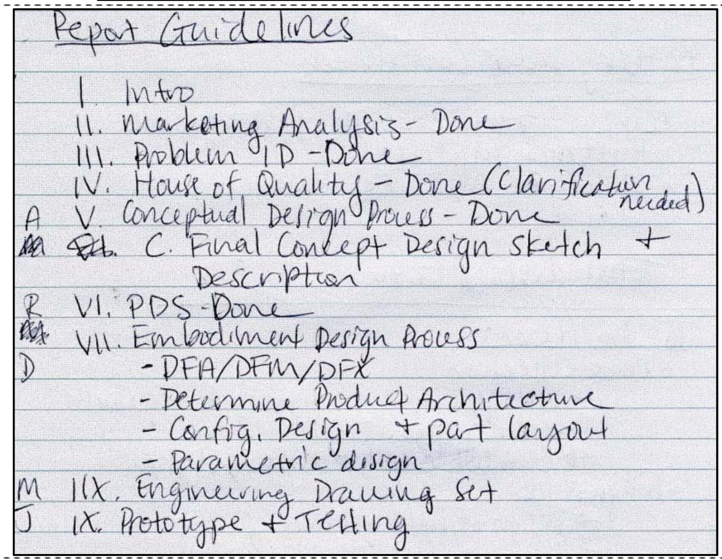
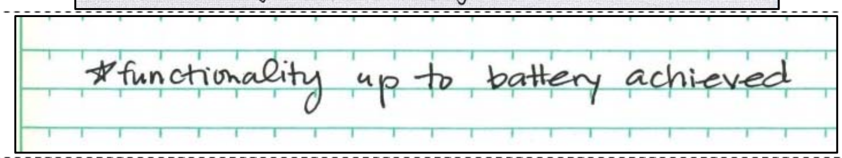


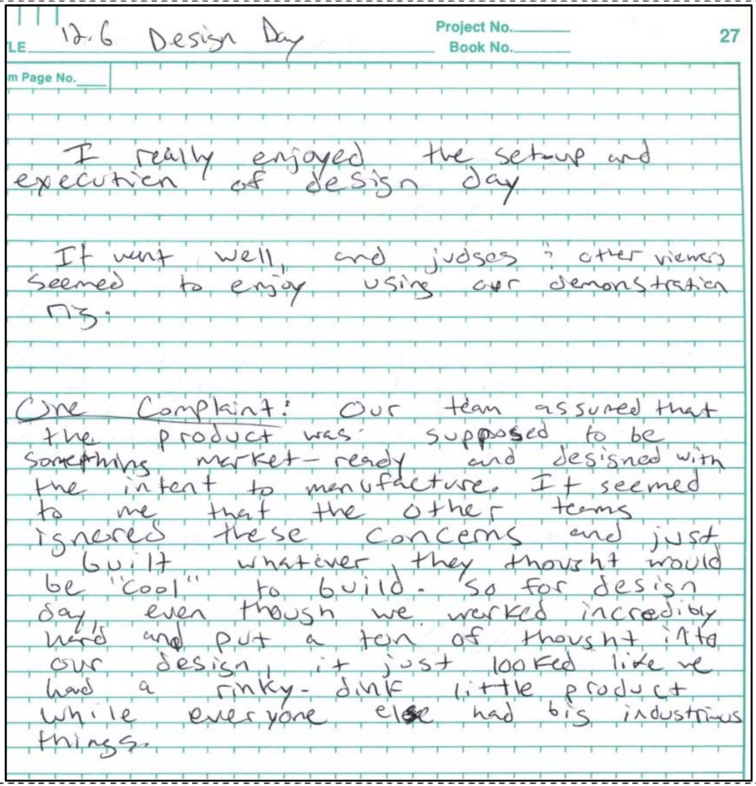
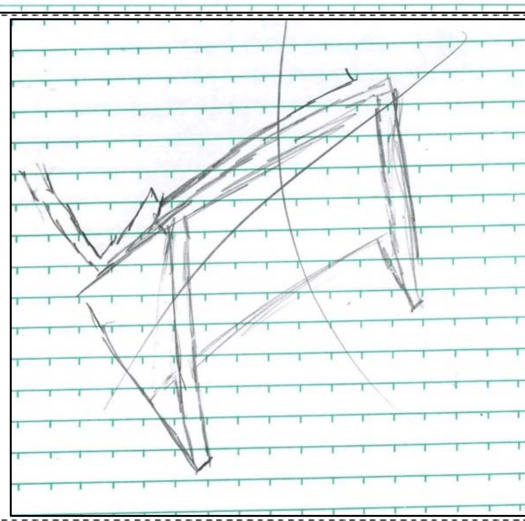
Note: I really liked the format of the prototyping presentations. They were short enough that I felt engaged & interested in each one

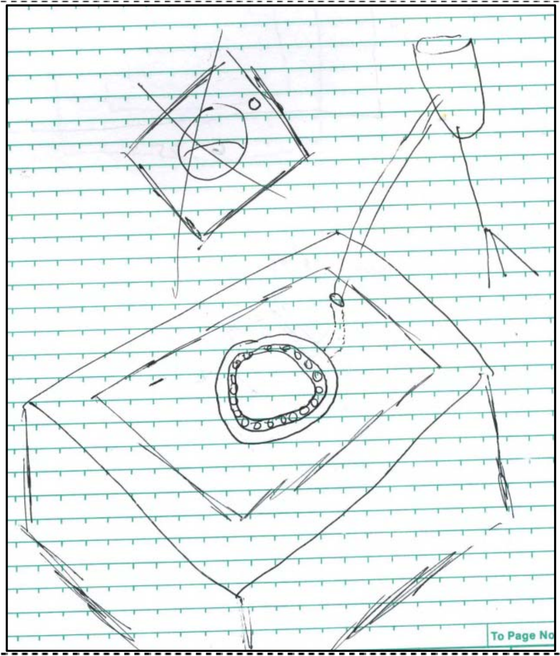
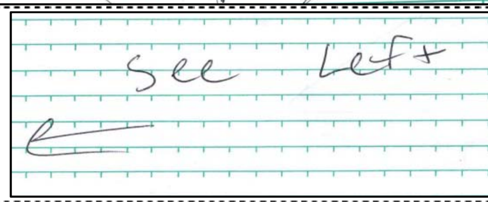
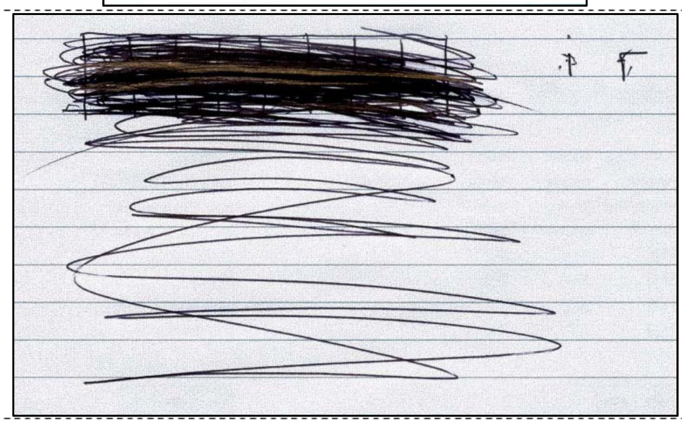
Design Process Notes(20)	Needs not met: - convienience of integrated charging in tent - tent with integrated lights / red light - red light doesn't effect light adaptation of eye in dark, - takes about 30 min to see best in dark with cones and rods in eye - red light has longest, slowest wavelength of any visible light and least energy - blue light high freq. / engy - infrared is lower form but invisible to e - not bulky, water proof. - Flexible
	Describe your final Prototype + functionality - Very close to ~~original~~ what the final design ~~go~~ would appear - ~~Demonstrates the~~ ~~more~~ - Shows an increase in stability ~~with de~~ during ~~of~~ coring into concrete - ~~other~~ Demonstrates only one size. (1 3/4" bit) - Feasability of the standing on concept - Rotatable
To Do Lists (21)	To do items - Measure voltage output of dynamo @ riding speeds (variable) - Current output of dynamo - Begin design of housing/mounting - Procure battery
	To do list: Thursday - Meet to finalize concepts Friday -> Got drill Saturday Sunday - test? Monday - Tuesday - 9 final concepts

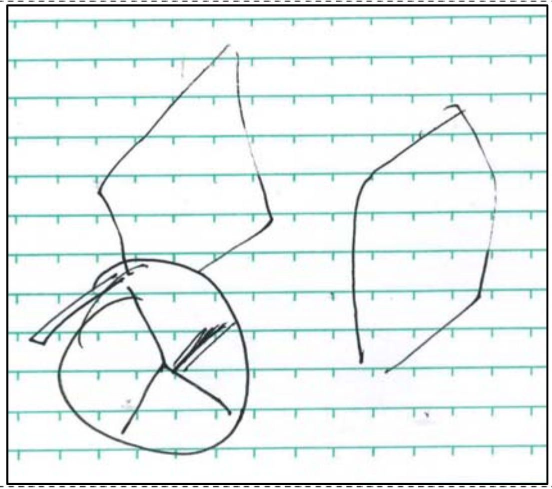
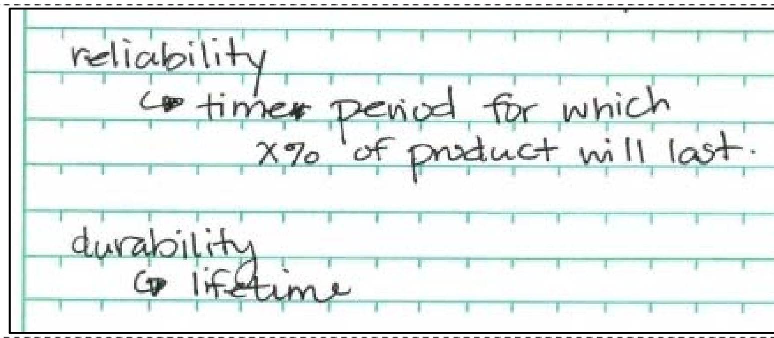
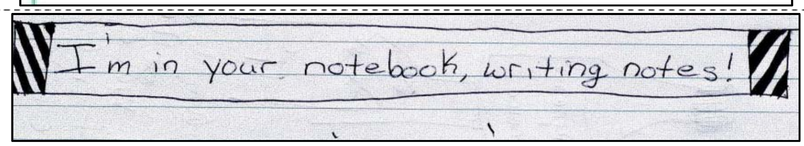
Revelations (22)	~~Grip~~ Despite all its positive points the Full Drill Clamp Design does have some negative ~~aspects~~. characteristics. ~~The mech~~ While the clamp which ~~encompasses the~~ grips the drill during cutting allows for a variety of different drills to be used in conjuction with the support, it is possible that ~~these parts the clamp in particular would be would a high cost a significant amount~~ to manufacture due to its curved shap ~~and complex~~ ve the intersection between the clamp and vertical support could concentrate forces ~~resu~~ reacting to either vibrations or the ~~forces~~ holding force necessary to support the actual drill. To Page No.
	There are some product constraints that are not presented in the House of Quality that are still very important characteristics. Specifically, safety is a factor which should always be designed for. Additionally, the support system should aim to support a variety of brands of saws and different sizes of drill bits.
Meeting Notes (23)	TUESDAY MEETING EXEC. SUMMARY - KAT MARKET - MARY PDS - KATHY, PROBLEM ID. HOQ - JESS CONCEPT. DESIGN - KAT EMBODY - JESS PROTO. TEST - ANTHONY COST ANALYSIS - MARY APPENDIX - KATHY REFERENCES - ANTHONY.

	 meeting goals → find what to do about mount if prototyping → achieve charging in following order wheel: dynamo → rear casing: rectifier, battery charger ↓ battery ↓ USB (minty boost) → handlebar casing OR seat pouch: ~~minty boost~~ device → complete accounting. → acquire minty boost.
Task Assignments (24)	 Deadlines: May 3 – Poster. May 10 – Final Report.
	 - Report - Due April 5th → Key Subsystem section (part list, part drawings, subsy. drawing) → DFA, DFM
Inventory(25)	 Battery order Confirmed • Li-ion 7.4V 2200mAh Rechargeable Battery module • 4 Cell Li-PO/Li-Fe Battery charger Total Cost: $47.96
Price Quotes (26)	

	 EXISTING PRODUCTS $80 – 270 ea COMPLAINTS: NOT WATERPROOF BATTERY OPERATED BULKY EXPENSIVE TOUCHPADS NOT RELIABLE NO FEEDBACK HOW TO BENCHMARK ?? - TOO EXPENSIVE AMAZON REVIEWS EXISTING LOCKS ~ $2
Task Completion (27)	 Report Guidelines I. Intro II. Marketing Analysis - Done III. Problem ID - Done IV. House of Quality - Done (Clarification needed) A V. Conceptual Design Process - Done C. Final Concept Design sketch + Description R VI. PDS - Done VII. Embodiment Design Process D - DFA/DFM/DFX - Determine Product Architecture - Config. Design + part layout - Parametric design M IIX. Engineering Drawing Set J IX. Prototype + Testing
	 *functionality up to battery achieved
Project Milestones (28)	

Field Trip Notes (29)	 12.6 Design Day Project No. Book No. 27 Page No. I really enjoyed the setup and execution of design day It went well, and judges & other viewers seemed to enjoy using our demonstration rig. One Complaint: Our team assumed that the product was supposed to be something market-ready and designed with the intent to manufacture. It seemed to me that the other teams ignored these concerns and just built whatever they thought would be "cool" to build. So for design day, even though we worked incredibly hard and put a ton of thought into our design, it just looked like we had a rinky-dink little product while everyone else had big industrious things.
Mistakes (30)	

	
Cross References (31)	
Illegible Entries (33)	

	
Designer Signature (34)	
Definitions (36)	
Other/ No Evidence of Cognitive Activity (35)	

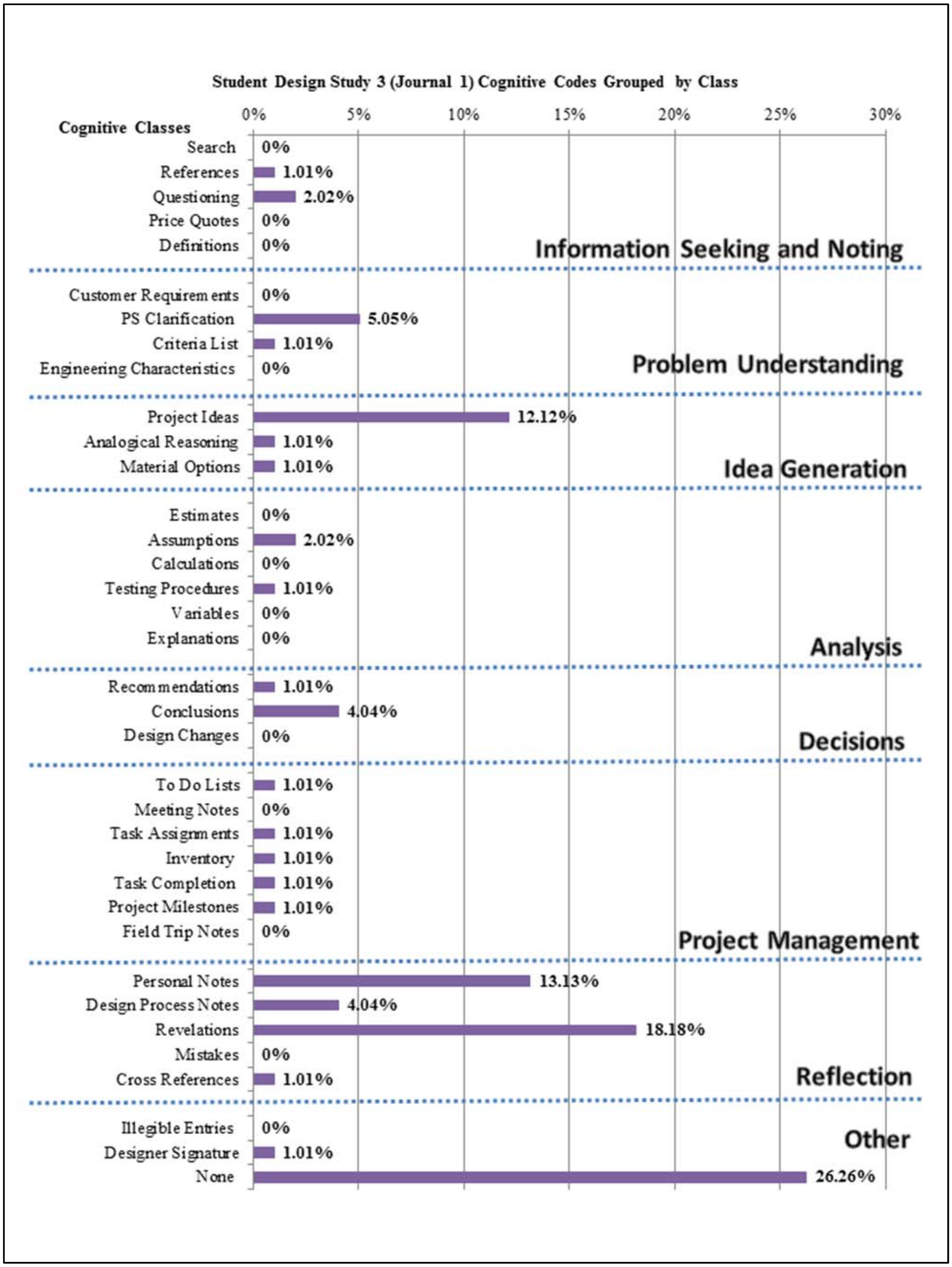


Figure 69: Student Design Study 3 (Journal 1) Cognitive Code Results by Class

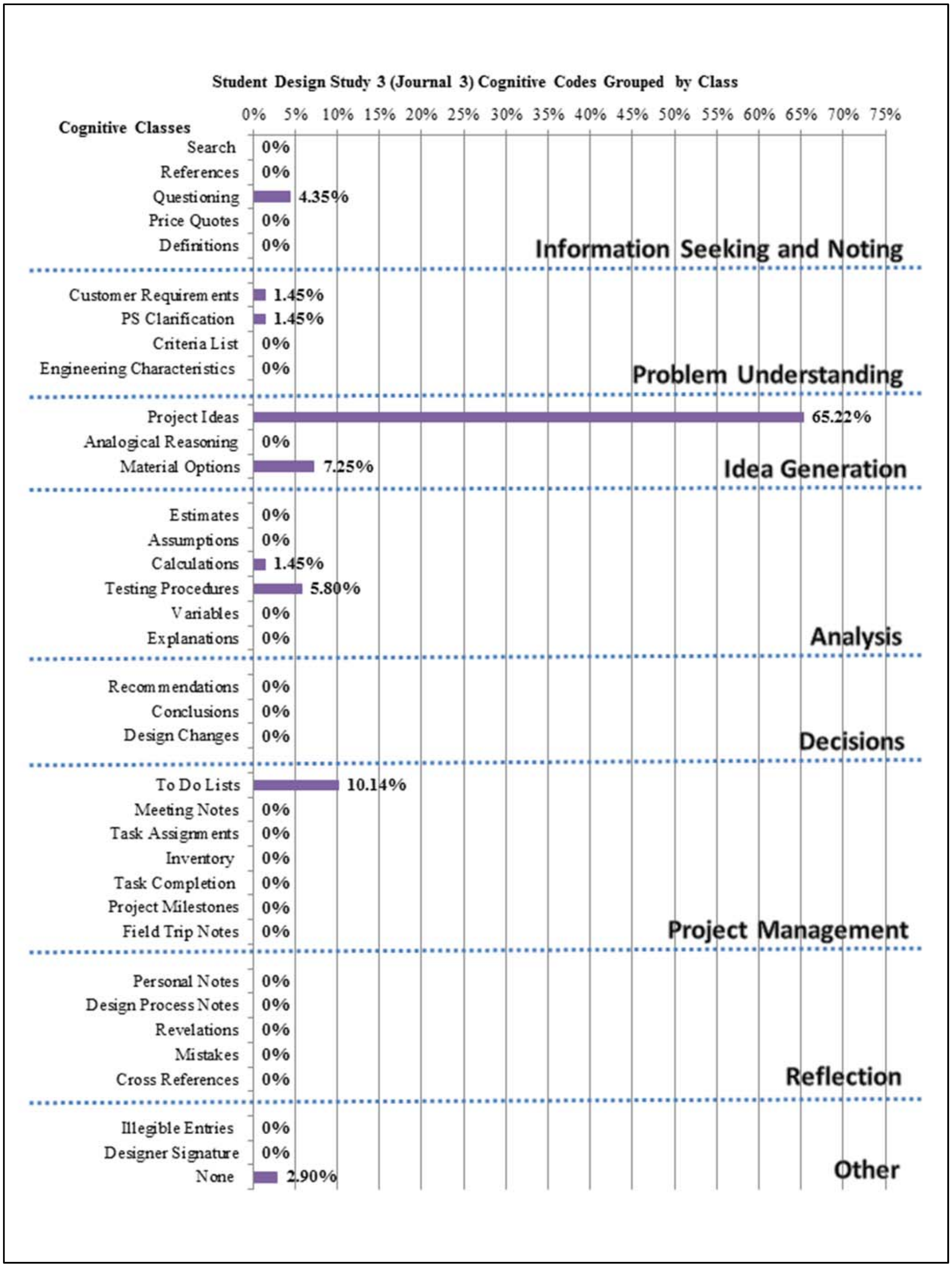


Figure 70: Student Design Study 3 (Journal 3) Cognitive Code Results by Class

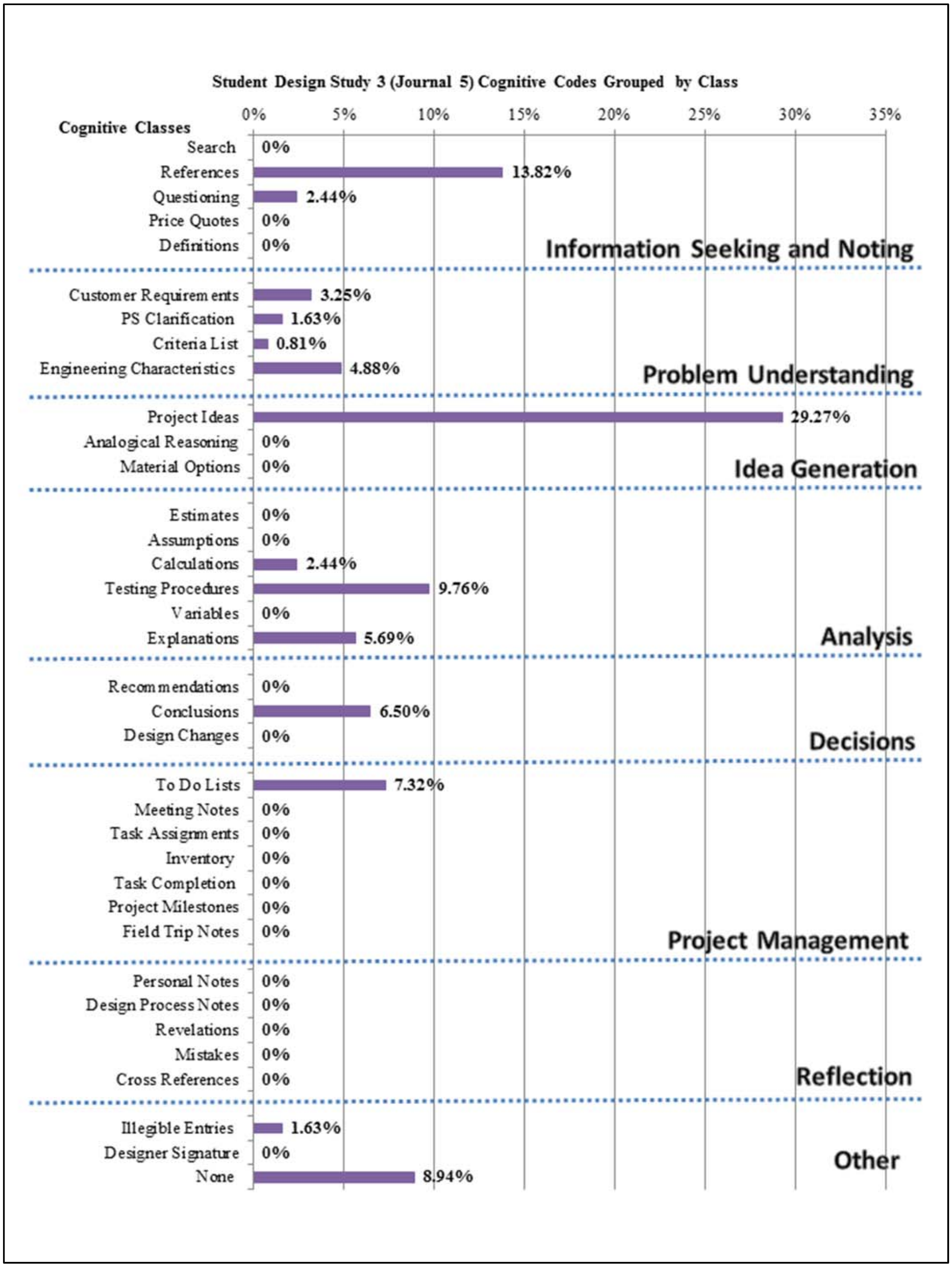


Figure 71: Student Design Study 3 (Journal 5) Cognitive Code Results by Class

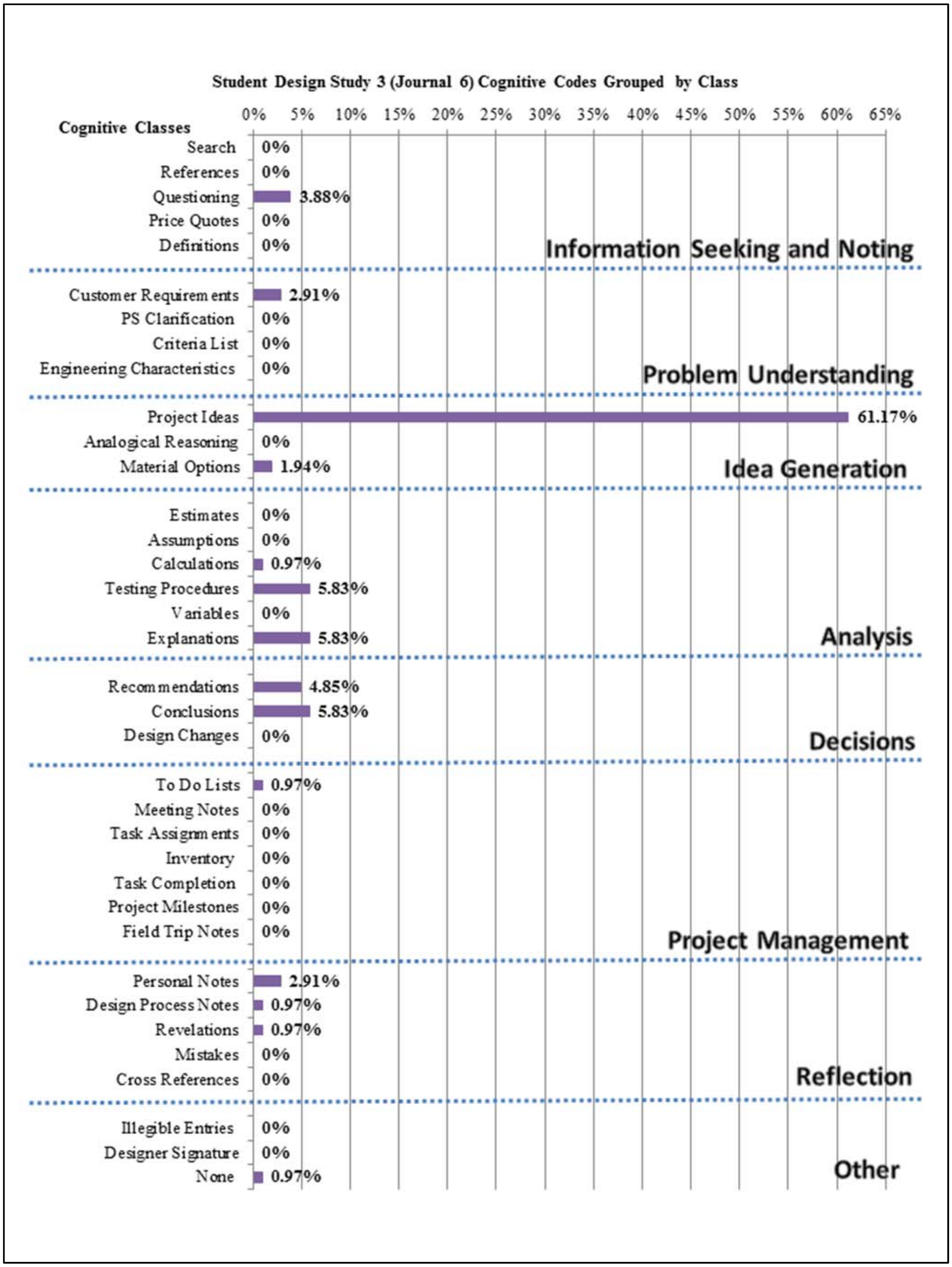


Figure 72: Student Design Study 3 (Journal 6) Cognitive Code Results by Class

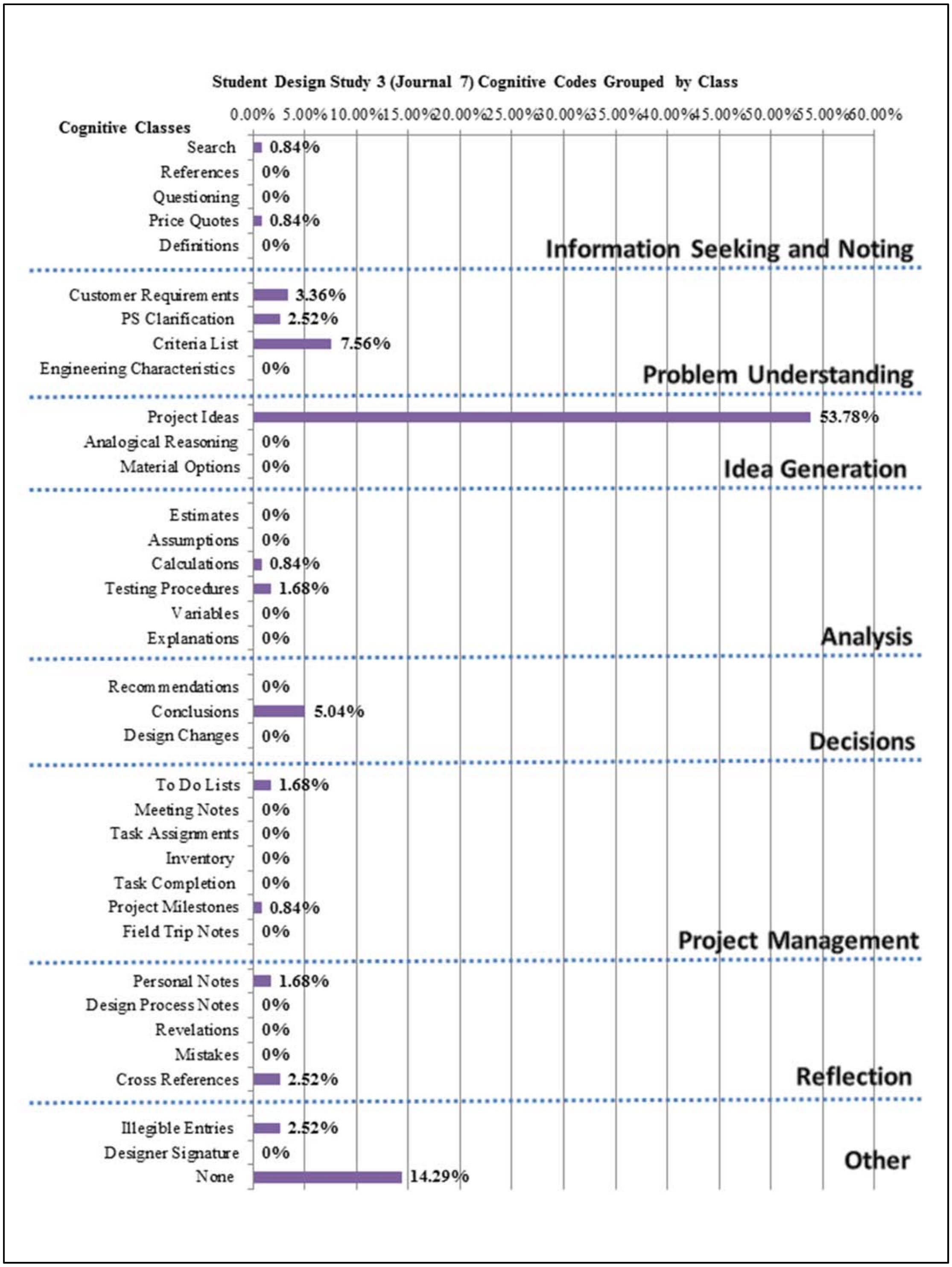


Figure 73: Student Design Study 3 (Journal 7) Cognitive Code Results by Class

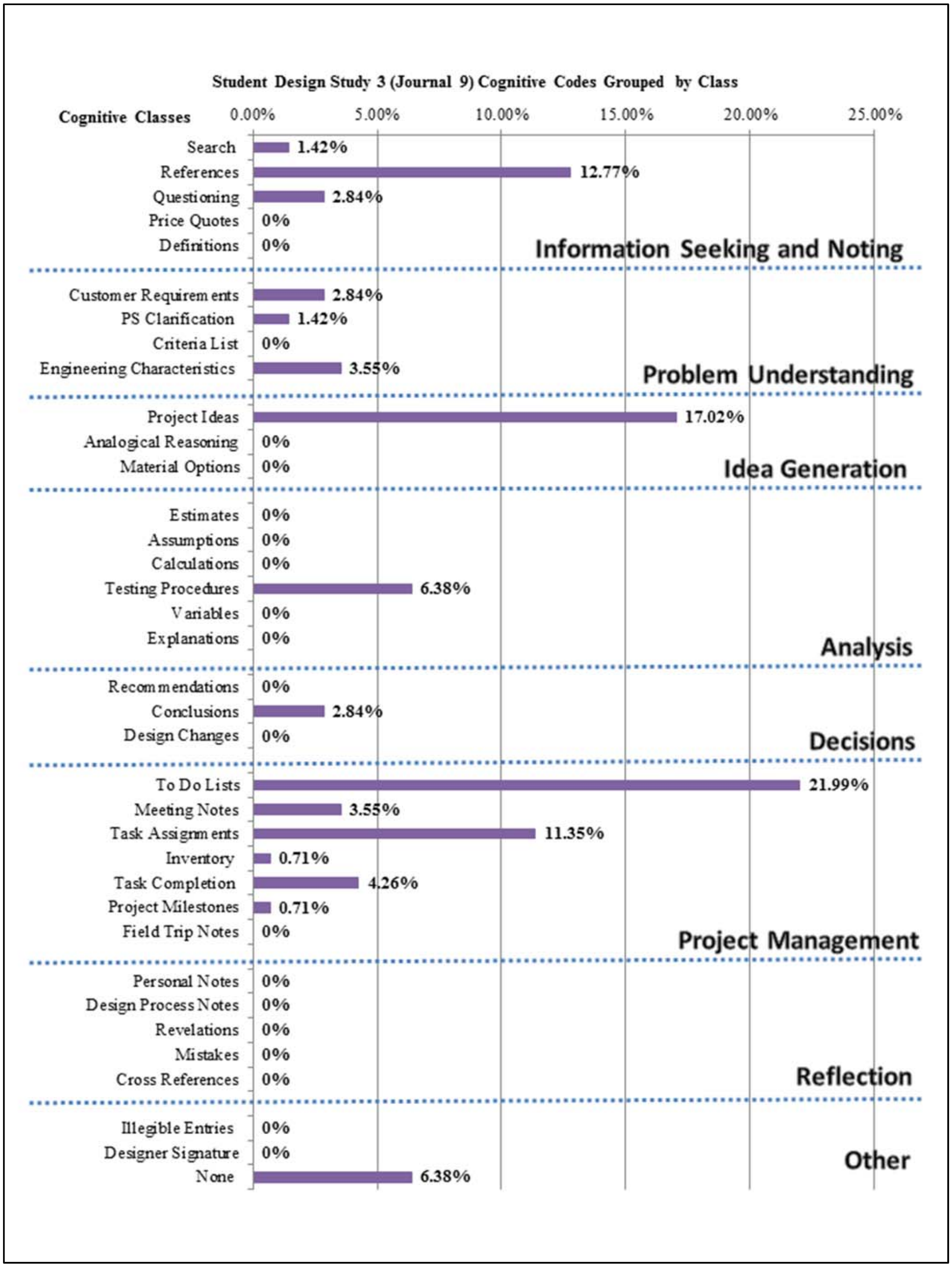


Figure 74: Student Design Study 3 (Journal 9) Cognitive Code Results by Class

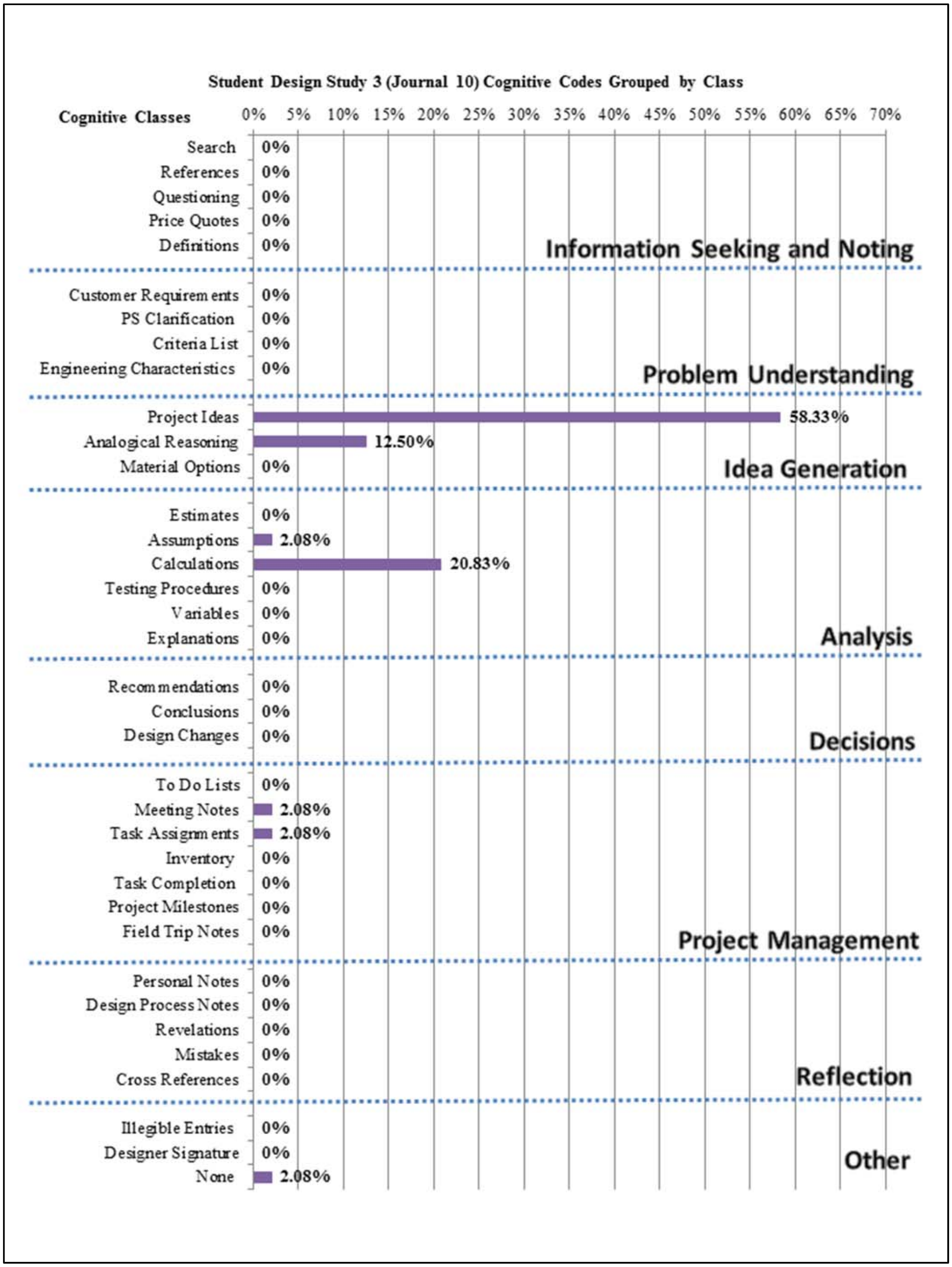


Figure 75: Student Design Study 3 (Journal 10) Cognitive Code Results by Class

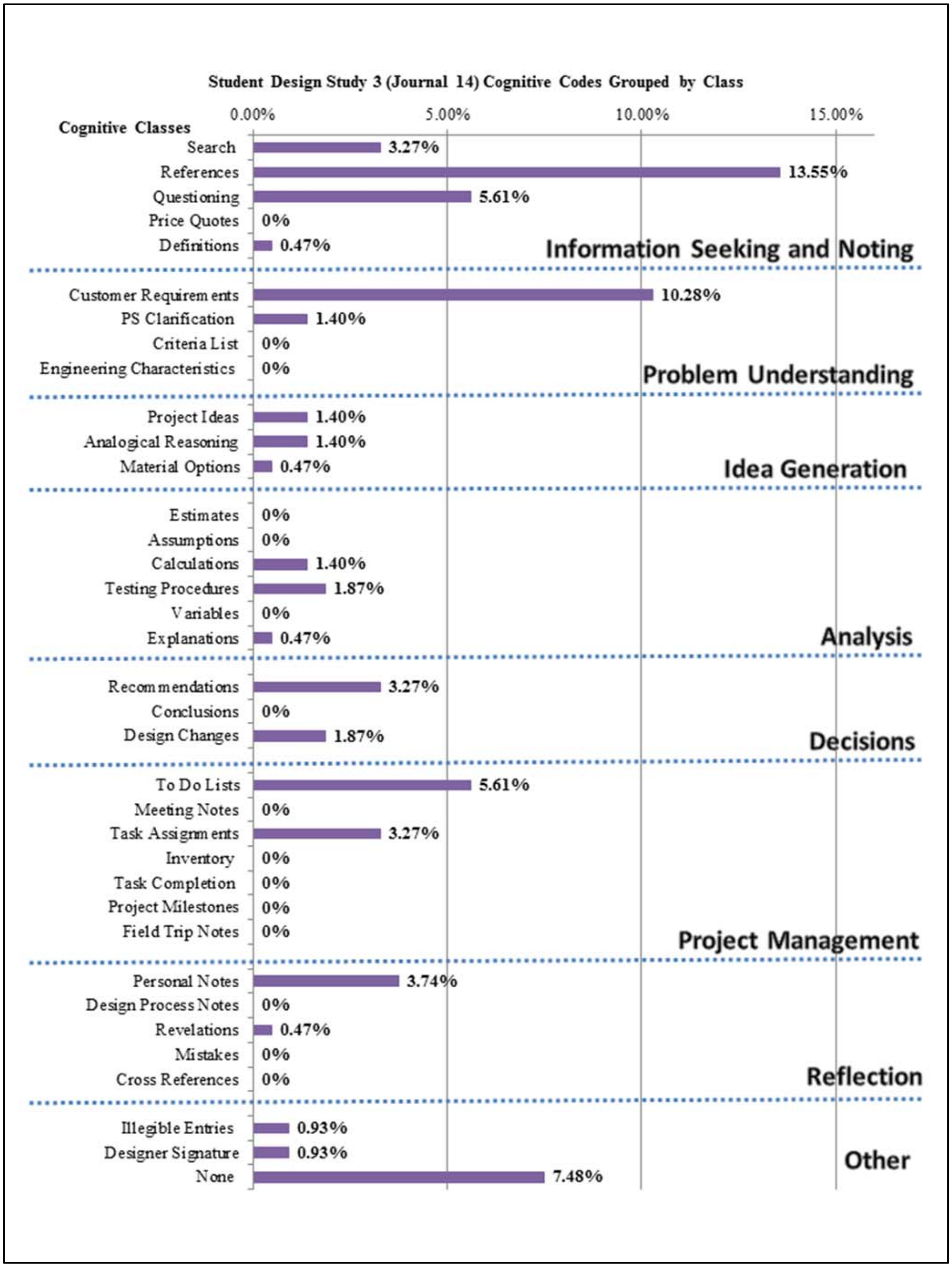


Figure 76: Student Design Study 3 (Journal 14) Cognitive Code Results by Class

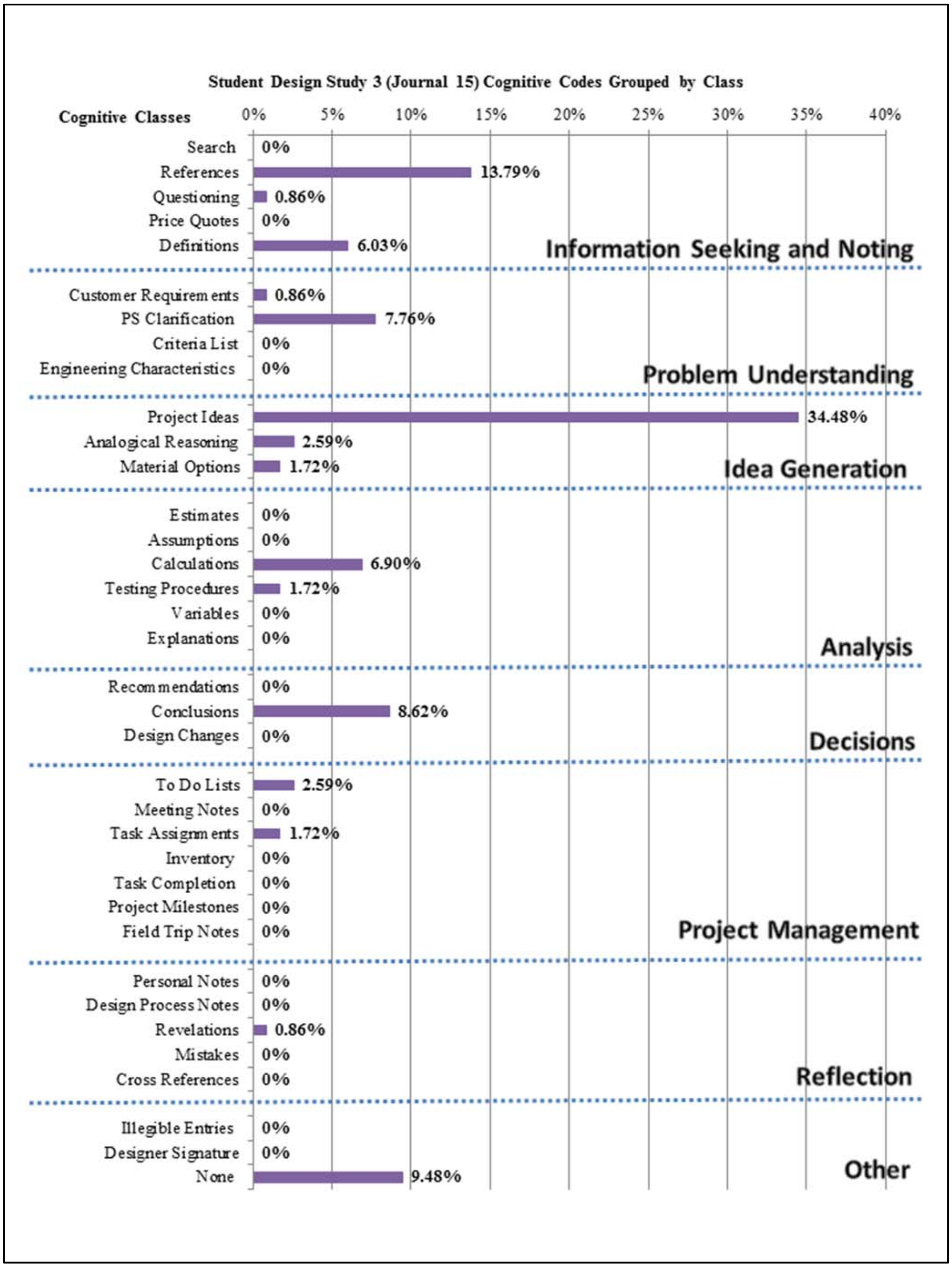


Figure 77: Student Design Study 3 (Journal 15) Cognitive Code Results by Class

Glossary

Lab Notebook- A permanent records of a scientists or engineers lab research work created with a formal process of specifying stages of the scientific method and recording the successes and failures. A lab notebook is usually kept in a *Confidential* bound notebook with graph style green and white paper including the labels project number, book number, title, date, witnessed and understood by me, invented by, recorded by, and page numbers. Historically presented as proof of first to concept in cases where patent disputes were handled in a court of law.

Design Journal- A formal record of text and visual representations during a design process usually kept in a bound notebook with pages numbered and dated. The design journals are a place to sketch concept drawings, write notes, make lists, record reflections, and document design decisions. The design journal is a tool for engineers and inventors to use for reflecting on the design process, prior analysis, and personal reflections relating to the product being designed.

Personal Journal- A informal record with distinct entries that reports daily thoughts and feelings about events usually kept in bound notebook with blank lined pages. The content of a personal journal is usually considered confidential and used for self-reflection and personal growth.

Cognitive Activities- In engineering design cognitive activities are defined as a set of activities that are stimulated by design requirements and design tasks and end up at the conclusion of the product design process. Cognitive activities include cognitive processes and mental activities such as perception, thinking, etc. [104]

Verbal Protocol Study – A method of having participants in a study "talks aloud" while they are performing a specific task. It is thought that this form of talking while performing mirrors the cognitive activity stream and therefore allows researchers to have access to the mind while also allowing the participant to alleviate space in their working memory[105]. Verbal protocol analysis can be applied in a variety of research settings and disciplines.

Metacognition- Meta-cognition, an intentional monitoring of cognitive activities, can be used as a guide to knowledge reuse [104].

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19. Shah, J., Kulkarni, S.V., and Vargas-Hernandez, N. , *Evaluation of Idea Generation Methods for Conceptual Design: Effectiveness Metrics and Design of Experiments* Journal of Mechanical Design, 2000. **122**(4): p. 377-384.
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Curriculum Vitae

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EDUCATION

University of Maryland (College Park, MD)

PhD in Mechanical Engineering- Advanced to Candidacy June 1, 2011
Graduation Expected May 2012
Dissertation Title: "Design Thinking: Cognitive Patterns in Engineering Design Documentation"
MS in Mechanical Engineering- December 2011

Georgia Institute of Technology (Atlanta, GA)

BS in Mechanical Engineering- May 2003

Clark Atlanta University (Atlanta, GA)

BS in General Engineering- May 2003

RESEARCH EXPERIENCE

Graduate Research Assistant September 2007- present
Design and Reliability Research Group Advisor: Dr. Linda Schmidt
Researched the cognitive task of student design teams during Capstone Design (Integrated Product and Process Development) courses by analysis engineering design documentation. Created a cognitive coding scheme to categorize and analyze the date found in student recorded design journals from senior capstone design courses. Analyzed capstone design reports visual representations highlighting the benefit of sketching during the mechanical design process. Researched coding schemes for mechanical design and applied sketch coding schemes found in literature to capstone design final reports.

Student Researcher May 2002- August 2002
Georgia Institute of Technology S.U.R.E. Program Advisor: Dr. Peter Hesketh
Optimized the fabrication of hydrogel-based microvalves in the microelectromechanical systems (MEMS) research group. The National Science Foundation supports this research program.

Student Researcher January 2001- May 2001
Clark Atlanta University
Researched the temperature effects of Fiber Reinforced Polymers (FRP's) on masonry structures in various climates throughout the world. The United States Army supported this research project.

PROFESSIONAL EXPERIENCE

Program Coordinator, Bridge Program Spring 2008-Spring 2010
University of Maryland- College Park
Coordinated the planning and implementation of a 5-week residential program for 2-pre-freshmen, including opening reception and closing awards reception. Provided support for academic programs aimed toward increasing the participation and graduation rates of African American, Hispanic, and Native American students in engineering. Managed a staff of 6 student workers, managed a $40,000 budget, served as academic advisor for course scheduling and midterm reviews.

Engineering Design Instructor July 2004 – June 2007
Grantham Academy for Engineering
Taught basic fundamentals of engineering including electrical, mechanical, civil, and architectural to 7th and 8th grade students. Developed 7th and 8th grade curriculum according to Texas Essential Knowledge and Skills (TEKS) for 300 students over a 3 year period utilizing Project Lead the Way, Inc.'s Gateway to Technology. Founded the school's Energy Education Engineer's Program in 2006 with an award of $10,000 from BP Amoco to promote energy awareness among the students and the community.

Instructional Aide August 2003- May 2004
Cobb County School District
Worked as a classroom aide at Pebblebrook High School for students with behavior and academic challenges.

Mechanical Engineering Intern May 2001- August 2001
BP Amoco Exploration and Production Division
Worked in the inspections department as a pipeline inspector, Gained field experience in vessel inspection procedures

Mechanical Engineering Intern May 1999 – August 2000 (2 summers)
Williams Gas Pipeline Company
Worked in the compressor and controls services department on automation of compressor stations throughout the company's pipeline system. Also designed human interface screens for pressure valve automation. (2000) Designed a wastewater treatment system for Compressor Station #35. Implemented and installed the wastewater treatment system. (1999)

Petroleum Engineering Intern May 1998- August 1998
Texaco, Inc.
Performed water separation testing of chemicals on crude oil from the ocean.

REFEREED JOURNAL PUBLICATIONS

1. **Westmoreland, S.**, and Schmidt, L., (2011) "Findings from a Design Journal Pilot Study to Reveal Cognitive Behavior in Engineering Design Teams", *Under Review, Submitted to Journal of Mechanical Design, July 29,2011*

2. **Westmoreland, S.**, Ruocco, A., and Schmidt, L., (2011), "Analysis of Capstone Design Reports: Visual Representations", *Journal of Mechanical Design*, 133(5)

CONFERENCE PROCEEDINGS

1. **Westmoreland, S.**, and Schmidt, L., (2010), "What Engineering Designers Leave Behind: Developing a Cognitive Coding Scheme for Student Design Journals", *International Mechanical Engineering Congress and Exposition*, Vancouver, British Columbia, Canada, November 12-18, 2010.

2. Grenier, A., **Westmoreland, S.**, and Schmidt, L., (2009), "Sketching in Design: Easily Influencing Behavior", *American Society of Mechanical Engineers Design Engineering Technical Conferences and Computer Information in Engineering Conference*, San Diego, California, August 30 – September 2.

3. **Westmoreland, S.**, Grenier, A., and Schmidt, L. (2009), "Sketching During Mechanical Design: Studying Sketching at The University of Maryland", *American Society for Engineering Education Annual Conference and Exposition*, Austin, Texas, June 14- June 17.

4. **Westmoreland, S.**, Grenier, A., and Schmidt, L., (2008), "Analysis of Capstone Design Reports: Visual Representations", *American Society of Mechanical Engineers Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, New York, New York, August 3 – August 6.

GRANTS

1. Title: Maryland System Louis Stokes Alliance for Minority Participation 2008-2010 Bridge to the Doctorate- BD Site: University of Maryland- College Park
   Sponsoring Agency: National Science Foundation Division of Human Resource Development
   Amount Funded: $987,000.00
   Date: August 2008
   Role: Document Revisions, Collecting and Updating Current BD Statistics, Formatting, and Reviewing

WORKING PUBLICATIONS

1. **Westmoreland, S.**, (2012), "Expository Writing as a Tool for Teaching Cognitive Strategies and Expertise Development for Students in Engineering Design Courses, to be submitted to National Science Foundation as a CAREER Grant proposal

2. **Westmoreland, S.**, and Schmidt, L. (2012), "A Professional Engineering Design Journal: Analyzing Designer Documentation to Understanding Cognitive Design Sequences" , Design Studies, Submission Date: January 2012

3. **Westmoreland, S.**, and Schmidt, L. (2011), "A Comparison of Engineering Students and One Professional's Use of a Design journal: A Quantitative Study of Differences" , Journal of Engineering Education, Submission Date: December 2011

4. **Westmoreland, S.**, and Schmidt, L. (2012), "Measuring Differences: Identifying Contrasts between Journals written by Student Designers and a Professional Designer", American Society of Mechanical Engineers Design Engineering

Technical Conferences and Computer Information in Engineering Conference, Chicago, Illinois, August 12-15, 2012, Submission Date: January 27, 2012

5. **Westmoreland, S.**, and Schmidt, L. (2012), "Cognitive Evidence in Engineering Design Documentation: Results from a 3-Semester Design Journal Study", American Society of Mechanical Engineers Design Engineering Technical Conferences and Computer Information in Engineering Conference, Chicago, Illinois, August 12-15, 2012, Submission Date: January 27, 2012

6. **Westmoreland, S.** and Schmidt, L. (2012), "Cognitive Coding Scheme for Analyzing Design Activity", Fifth International Conference on Design Computing and Cognition DCC '12, June 7-9, 2012, *Under review- Draft paper submitted on January 20, 2012*

PRESENTATIONS

1. **Westmoreland, S.** (2010), "What Engineering Designers Leave Behind: Developing a Cognitive Coding Scheme for Student Design Journals", *International Mechanical Engineering Congress and Exposition*, Vancouver, British Columbia, Canada, November 12-18, 2010.

2. **Westmoreland, S.** (2009), "Sketching During Mechanical Design: Studying Sketching at The University of Maryland", *American Society for Engineering Education Annual Conference and Exposition*, Austin, Texas, June 14- June 17.

3. **Westmoreland, S.** (2008), "Analysis of Capstone Design Reports: Visual Representations", *American Society of Mechanical Engineers Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, New York, New York, August 3 – August 6.

POSTERS

1. **Westmoreland, S.** (2010), "Design Thinking: Cognitive Patterns in Engineering Design Documentation", LSAMP Poster Session, Rayburn Building on Capitol Hill, Washington, DC.

2. **Westmoreland, S.** (2008), "An Engineers Perspective: Searching Engineering Design Methods", National Black Graduate Student Association Conference, Chicago, Illinois, March. Also at National Society of Black Engineers 34th Annual Convention, Orlando, Florida, March.

UNIVERSITY TEACHING

Teaching Assistant Fall 2009- Fall 2011 (5 Semesters)
University of Maryland- College Park
Teaching assistant for ENME 472- Integrated Product and Process Development, a senior design course offered by the Department of Mechanical Engineering. Participated in lab sessions, team meetings, grading assignments, and evaluating teams at Mechanical Engineering Design Day competition. Lectures given: Analytical Hierarchy Process (AHP) for selecting among design alternatives and Technical Written and Oral Communication Skills.

Future Faculty Teaching Practicum Spring 2011
University of Maryland- College Park
Co-taught a course, ENME 472- Integrated Product and Process Development, under the supervision of Dr. Linda Schmidt. Prepared and presented lectures, mentored and supervised 2 design teams, graded assignments, and evaluated the students in the course. Lectures given on: Analytical Hierarchy Process (APH) for Selection Among Design Alternatives, Product Development Process (PDP), Manufacturing Costs, and Setting Design Parameters.

Course Instructor, Bridge Program Spring 2008- Spring 2010
University of Maryland- College Park
Course instructor for CMPS 299T and CMPS299B a seminar experience course for freshman students in the Bridge Program. Introduced students to the historical and contemporary academic excellence philosophies, competencies, and practices.

UNIVERSITY SERVICE

1. Mechanical Engineering Design Day Co-Coordinator- an event held each semester to present the senior capstone projects, prototypes, and teams to the campus community. Projects are judged by professors in mechanical engineering and also votes given by students for a “People’s Choice” award.
    a. Spring 2010- 17 teams
    b. Fall 2010- 17 teams
    c. Spring 2011- 19 teams
    d. Fall 2011- 15 teams

2. PROMISE , Maryland’s Alliance for Graduate Education and the Professoriate Peer Mentoring Program (Fall 2007- Spring 2011) 1st year protégé, 2nd year and beyond Peer Mentor, and frequent panelist speaker for prospective students.

3. Black Engineers Society (Fall 2007- present) Graduate Student Coordinator, Undergraduate Mentor, Graduate Student Initiatives Committee Chair, NSBE Leadership Certified, Research and Technical Development Coordinator for National Academic Excellence Committee, TORCH Center Volunteer, PCI Volunteer.

4. F.R.E.E. (Focusing Research on Entrepreneurial Empowerment) Poster Session Chair and Organizer (Spring 2009) F.R.E.E. was organized with a grant awarded by Pepsi, Inc. to showcase research and entrepreneurial activities and accomplishments of graduate and undergraduate members of the Black Engineers Society.

5. Graduate Research Interactions Day (G.R.I.D.) Judge (Spring 2008).

6. Center for Minorities in Science and Engineering Volunteer (Fall 2007- present) Winter Leadership Retreat, Annual Student Recognition and Alumni Banquet.

PROFESSIONAL SOCIETIES

1. American Society of Mechanical Engineers (ASME)
   - Student Member (2007- present)
   - Design Engineering Division- Broadening Participation Committee Member (2011- present)
   - Paper Reviewer- 2011 International Design Engineering Technical Conference & Computers and Information in Engineering Conference
2. American Society for Engineering Education (ASEE)
   - Student Member (2007- present)
3. National Society of Black Engineers (NSBE)
   - Student Member (1998 – present)
4. Society of Women Engineers (SWE)
   - Student Member (2007- present)

SERVICE ORGANIZATIONS

1. Alpha Kappa Alpha Sorority, Inc. (AKA)
   - Member (1999- present)
2. Clark Atlanta University Alumni Association
   - Life Member (2009 – present)
3. Georgia Institute of Technology Alumni Association
   - Annual Roll Call Supporter (2003- present)
4. Smithsonian National Museum of African American History and Culture
   - Volunteer (2009-2011)
   - Docent (2011- present)
5. The Mademoiselles Alumnae, Inc.
   - Mademoiselle Annual Conference Registration Chair (2005- present)

FELLOWSHIPS

1. National Science Foundation LSAMP *Bridge to the Doctorate* Fellowship (2007)
2. National Action Council for Minorities Alfred P. Sloan PhD Fellowship (2009)
3. Alpha Kappa Alpha Sorority, Inc. Educational Advancement Foundation *Graduate Merit Award* (2008)

DISTINGUISHED AWARDS

1. 13^{th} Annual NSBE Golden Torch Award: Mike Shinn Distinguished Member of the Year (Female), 2010
2. 13^{th} Annual NSBE Golden Torch Award: Graduate Student of The Year, 2010
3. Outstanding Graduate Student Award, Black Engineers Society, 2009
4. Outstanding Service Award, Center for Minorities in Science and Engineering, 2009
5. Mechanical Engineering Certificate of Excellence, 2008, 2009, 2010

PROFESSIONAL DEVELOPMENT

1. A. James Clark School of Engineering Future Faculty Program- 4th Cohort, January 2010- May 2011 (College Park, MD)
2. Howard University Preparing Future Faculty Summer Institute, June 2011 (Washington, DC)
3. 17th Annual Compact for Faculty Diversity Institute on Teaching and Mentoring, October 2010 (Tampa, FL)
4. 14th Annual Compact for Faculty Diversity Institute on Teaching and Mentoring, October 2007 (Arlington, VA)
5. 18th Annual Compact for Faculty Diversity Institute on Teaching and Mentoring, October 2011 (Atlanta, GA)
6. PROMISE Dissertation House- a series of workshops, meetings, and seminars that are held on college campuses and at conferences to facilitate successful completion of the doctoral degree, July 2010 (College Park, MD)
7. PROMISE Dissertation House,- a series of workshops, meetings, and seminars that are held on college campuses and at conferences to facilitate successful completion of the doctoral degree, July 2011 (College Park, MD)
8. Graduate Engineering Education Consortium for Students (GEECS)Symposium- 1st Cohort, March 2012 (Arlington, VA)