AC 2010-2331: INCUBATING ENGINEERS, HATCHING DESIGN THINKERS: MECHANICAL ENGINEERING STUDENTS LEARNING DESIGN THROUGH AMBIDEXTROUS WAYS OF THINKING

Micah Lande, Stanford University

Micah Lande is a Ph.D. candidate in Mechanical Engineering and Design at the Center for Design Research at Stanford University. He is researching how engineers learn and apply a design process to their work. Micah is a co-Editor-in-Chief of Ambidextrous, Stanford University's Journal in Design. His academic interests include design and engineering education, design thinking and foresight thinking, creativity and innovation, and interdisciplinarity and multidisciplinarity in higher education. Micah has a B.S in Engineering from Stanford's Product Design program and has a M.A. in Education from the Stanford School of Education program in Learning, Design and Technology.

Larry Leifer, Stanford University

Larry Leifer is a Professor of Mechanical Engineering Design and founding Director of the Center for Design Research (CDR) at Stanford University. A member of the faculty since 1976, he teaches the industry sponsored master's course ME310, "Global Project-Based Engineering Design, Innovation, and Development;" a thesis seminar, "Design Theory and Methodology Forum;" and a freshman seminar "Designing the Human Experience." Research themes include: 1) creating collaborative engineering design environments for distributed product innovation teams; 2) instrumentation of that environment for design knowledge capture, indexing, reuse, and performance assessment; and 3), design-for-sustainable-wellbeing. His top development priority in the moment is the Hasso Plattner Design-Thinking-Research Program and associated "Electronic Colloquium on Design Thinking Research," a peer commentary journal.

Incubating Engineers, Hatching Design Thinkers: Mechanical Engineering Students Learning Design Through Ambidextrous Ways of Thinking

Abstract

Design Thinking and Engineering Thinking are complimentary yet distinct aspects of mechanical engineering design activities. This paper examines these distinctions in the context of mechanical engineering students designing in a project-based learning course at Stanford University. By qualitatively analyzing and plotting student teams' prototyping activities, the students' work patterns can generally be assessed along a framework of *Ambidextrous Ways of Thinking*.

Introduction

Innovation is a difficult challenge. Today, in technology product development, it often takes many players from many areas (business, engineering, etc.) working together to create something anew. Along the way, competing voices and values often surface from groups and individuals borne from their disciplinary and epistemic roots. The best equipped can navigate safely among these political issues.

This paper focuses on mechanical engineering design, and, in particular, Design Thinking and Engineering Thinking and how these activities may be distinguished. Design Thinking and Engineering Thinking are both vital aspects of mechanical engineering design activities and serve as underlying practices for doing and teaching innovation.

A theoretical framework relating these concepts and some findings are presented from empirical observations of what Design Thinking and Engineering Thinking activities look like in Mechanical Engineering 310 *Global Team-Based Design Innovation*, a year-long, project-based learning course at Stanford University, where graduate mechanical engineering students model industry work practice.

Distinctions between the Design Thinking and Engineering Thinking mindsets will be proposed and catalysts for mechanical engineering students learning design thinking will be presented. The implications herein point to educational benefits to mechanical engineering students developing judgment through an ambidextrous navigation of Design Thinking and Engineering Thinking activities.

Ambidextrous Ways of Thinking Framework

Previous efforts by the authors to classify student activities have produced this working framework modeling *Ambidextrous Ways of Thinking* [1] as accessed by mechanical engineering design students. As shown in Figure 1, it is visually represented as a matrix showing relative position of Design Thinking [2], Engineering Thinking [3 4], Production Thinking [5], and Future Thinking.[6] Along the Y-axis is a spectrum from incremental innovation to *breakthrough innovation*.[7] Along the X-axis it is measured in time, from short-term to long-term. The activity of Design Thinking can be to *solve a problem* with the end results being an *idea* created. For Engineering Thinking *making a solution* results in an *artifact or stuff*. Production Thinking allows for the *remaking of a solution* with the results being *facsimiles of stuff* or plans by which to make copies. Future Thinking allows one to *reset the problem* with the outcome being a *question*.

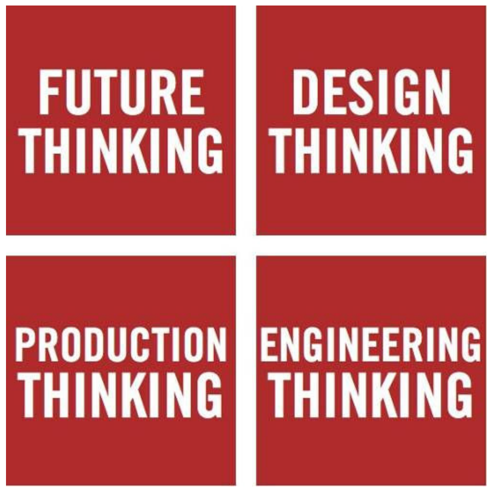

Figure 1. *Ambidextrous Ways of Thinking* framework.

Illustrative Product Examples

An attempt here is made to identify, define and distinguish Design Thinking activities from Engineering Thinking activities. An illustrative example (Figure 2) can compare both the features of and how users describe the Apple iPhone to the RIM Blackberry phones and experiences. For the iPhone, it is often said it is an elegant aesthetic, the user interface is lauded and its role as part of a larger product family ecosystem is mentioned. For the Blackberry it is the physical keyboard and a feature set that pushes e-mail to the device which is often highlighted. Here you can see this as tension between the functionality (iPhone) compared to the physicality (Blackberry). This distinction exemplifies a distinction between Design Thinking and Engineering Thinking.

Figure 2. Apple iPhone and RIM Blackberry as illustrative examples of Design Thinking and Engineering Thinking.

ME310 Course Context and Qualitative Research Methods

The course Mechanical Engineering 310 *Global Team-Based Design Innovation with Corporate Partners* [8 9 10] is a core mechanical engineering and design product-based-learning[11] course for first-year masters students in mechanical engineering. It features student teams working on corporate sponsored authentic industry design projects. Each academic year, the course features approximately 10 projects with student teams and corporate sponsors. Over time, prompts provided by sponsoring companies have evolved from manufacturing, testing, and assessment equipment to product focused problems [8]. In recent years, problems that industry have presented focus less on traditional mechanical engineering or mechanical design systems problems but rather more general wicked and ill-defined problems.

In situ observations of student engineers doing design was undertaken in the academic year 2008-2009. Ethnographic observations were undertaken in weekly student team meetings as well as weekly class section. Documentation analysis was done of student reports that were generated at the end of fall, winter, and spring quarters for 2007-2009.

The teams of mechanical engineering graduate students were observed during regular team meetings and their project reports analyzed. A researcher sat in on weekly team meetings and class presentations, gathering qualitative notes in situ (audio recordings and a subset of sessions were transcribed). Interim project reports detailing the design development of their work as well as the final specifications of their project were analyzed, a coding scheme using these student-reported reflections was used to map the student's experience to the *Ambidextrous Way of Thinking* metric (Figure 3) combining Design Thinking and Engineering Thinking activities and design process steps.

Figure 3. Weekly student design team meeting in Mechanical Engineering 310 course.

Differing Student Approaches to Designing and Engineering

The primary approaches of engineers and designers differ. For engineering students, to learn design is a hard task. They are adding Design Thinking processes to their already ensconced analytical engineering training and mental models of problem solving. It is often a new approach to problem solving and the ordering of project objectives are often difficult for students to make. For example, there are switches from *opportunity push* to *needs pull*, from physical-driven to function-driven, from a goal of minimizing uncertainty to preserving ambiguity.

Many undergraduate engineering curriculums are split between learning engineering content knowledge and its application. For introductory classes in the freshman and sophomore year, engineering problem-solving is paramount and individuals work on close ended problems in the form of problem sets. Upper-level classes focus, in contrast, on open-ended problems and working in groups, approximating work practice one might find in industry. For some students, the switch is harsh, or at least, seemingly arbitrary. For others, the change is welcome. Working on problems individually is much different than working in a team to solve some open-ended, authentic situation. Engineering education aims for engineers that can both better ask and answer questions and have prototyping skills and Design Thinking as part of their repertoire. By observing student engineers learning a design process in the safe environs of a master's level course, we can more easily follow and analyze their design activities than might be possible in an industry setting.

For mechanical engineering students, especially the cohort of master's students observed in the course of this study, their prior exposure to Design Thinking was mostly limited. They might have been exposed to Design Thinking and design activity through a capstone mechanical engineering course or had summer internship experiences in industry. Projects, though, often times were focused on mechanical engineering optimization and redesign tasks, mostly not inclusive of people in the system. In contrast, students' have more exposure to and experience with Engineering Thinking activities, or the implementation aspect of the design process, the focus of many of their prior engineering courses.

Case of Matched Pair of Design Projects

A pair of student projects (Figure 4) have been selected to compare and contrast their design processes. Both projects have similar starting points as *Amorphous Future* projects and end up as *Specific Design* projects. Students in Project *A*, done for Car Company, were tasked with designing the Automobile Copilot of the Future. Students in Project *B*, done for Consumer Products Company, were tasked with designing Very Human Technology. Applying the coding scheme using codes as nodes and connecting those with lines chronologically, it can be seen qualitatively how the activities of these project teams map. (This is shown in Figures 9 and 10.)

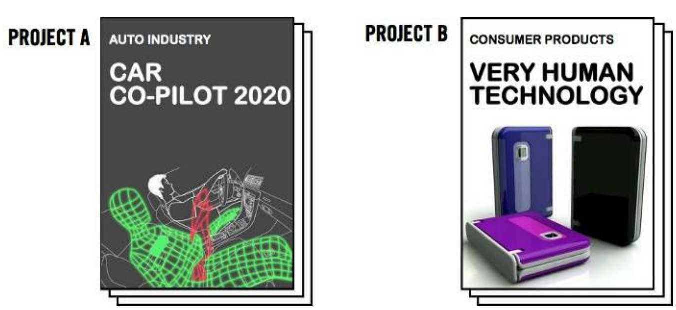

Figure 4. Example student design Project A and Project B.

Capturing Design Steps

By analyzing student documentation, it is feasible to capture the design steps that the student teams undertook. Previous research has described how general steps in the design process can be described. And much of that engineering education and design research focuses on what happens in the Design Thinking space. Atman and Bursic [12] looked at seven design textbooks and came up with a consensus list of steps in the design process. It is interesting to note that while Design Thinking in this context is described well enough (problem definition, identified need, gather info, modeling, feasibility, evaluation, decision) the Engineering Thinking space is described only by one term (implementation). Crawly [13] also uses implement to describe the Engineering Thinking space in his Conceive-Design-Implement-Operate model. These are summarized in Table 1.

CRAWLEY (2001)	ATMAN AND BURSIC (1998)
▪CONCEIVE	▪DEFINITION
▪DESIGN	▪IDENTIFY NEED
▪*IMPLEMENT*	▪GATHER INFO
▪OPERATE	▪MODELING
	▪FEASIBILTY
	▪EVALUATION
	▪DECISION
	▪*IMPLEMENTATION*

Table 1. Selected past efforts to define steps in a design process.

Table 2 lists the a priori coding scheme for prototyping activities applied to Project A and Project B student team projects.

FUTURE THINKING ACTIVITIES	**ENGINEERING THINKING ACTIVITY**
▪RESETTING	▪FUNCTIONAL PART PROTOTYPING
	▪FULL SYSTEM PROTOTYPING
DESIGN THINKING ACTIVITY	▪PRE-PRODUCTION PROTOTYPING
▪BENCHMARKING	
▪NEEDFINDING	**PRODUCTION THINKING ACTIVITY**
▪IDEATING	▪SENDING OUT
▪CONCEPTUAL PROTOTYPING	
▪EXPERIENCE PROTOTYPING	
▪TESTING	

Table 2. A priori coding scheme for team prototyping activities.

Figures 5 and 6 display the prototyping activities undertaken by each respective team. Table 3 lists the content focus of their prototyping activities.

Figure 5. Prototyping activities for Project A.

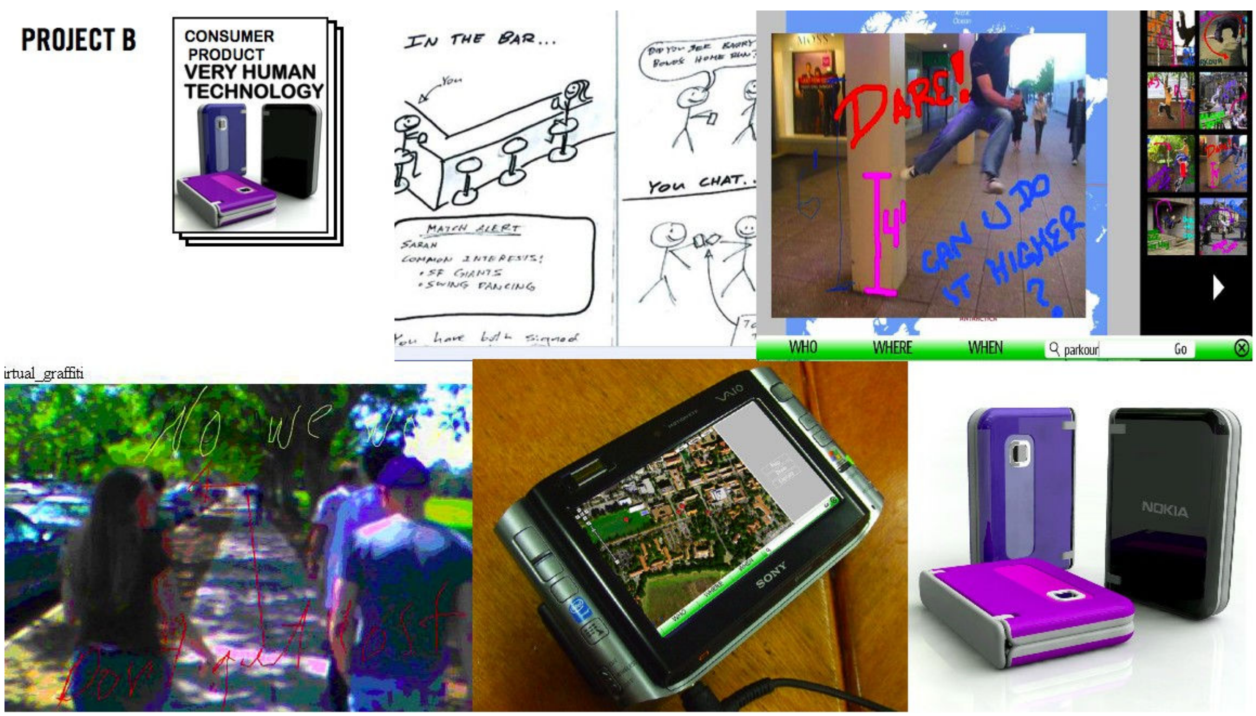

Figure 6. Prototyping activities for Project B.

PROJECT A
DESIGN STEPS

1. **BRIEF** *Nebulous Copilot*
2. **BENCHMARK**
3. **EXPERIENCE** *multi input, feature manager*
4. **IDEATE** *co-communicator*
5. **FUNCTIONAL PART** *real-time chat, info manager*
6. **RESET** *information processor*
7. **FUNCTIONAL PART** *information organizer*
8. **EXPERIENCE-TEST** *buttons, feedback*
9. **FUNCTIONAL PART** *audio alert*
10. **FUNCTIONAL PART** *audio visual outut*
11. **FUNCTIONAL PART** *generic voices*
12. **TEST**
13. **FUNCTIONAL SYSTEM** *vibrating buttons*
14. **SEND OUT** *fabrication*
15. **PRE-PRODUCTION PROTOTYPE**

PROJECT B
DESIGN STEPS

1. **BRIEF** *Very Human Technology*
2. **NEED** *interactions*
3. **IDEATE**
4. **EXPERIENCE** *shared environments*
5. **EXPERIENCE** *desirable screen*
6. **EXPERIENCE** *form factor*
7. **CONCEPTUAL** *storyboarding*
8. **CONCEPTUAL** *mobile commenting*
9. **BENCHMARK** *wireless*
10. **BENCHMARK** *RFID tags*
11. **PART** *table pc with interface*
12. **EXPERIENCE** *looks like*
13. **FUNCTIONAL** *works like*

Table 3. Prototyping activities project content for Project A and B.

Visualizing Design Steps

Figures 9 and 10 plot visualizations of the prototyping activities over time for Project A and Project B.

The students in Project A have iterated a number of times between Design Thinking activities and Engineering Thinking activities. Early on they redefine the scope of the project from a car copilot of 2020 towards something dealing more acutely with information processing, and towards the goal of having a preproduction prototype at the end of the course, even outsourcing some of the fabrication of parts.

For Project B, taking the same approach of coding the team's activities according to their self-reported design and development of the design process, coding those nodes connecting the lines it can be seen that the gross representation of the design is much different. The student team for Project B spent a lot of time benchmarking existing technology as well as drawing upon storyboards of possible experiences. Over the course of the year while students considered what very human technology meant they struggled to make much headway in redefining the project direction. Towards the end of the course students did choose a route that allowed them take their ideas and their design experiences out of the realm of just Design Thinking into Engineering Thinking and having physical tangible artifacts. Their work stopped short though of having a preproduction prototype. Their end result was a way finding and tagging system that used a handheld computer to mimic the functionality of their imagined device, as well as a form model of what it could look like. They did a works-like as well as a looks-like for a pair of final prototypes.

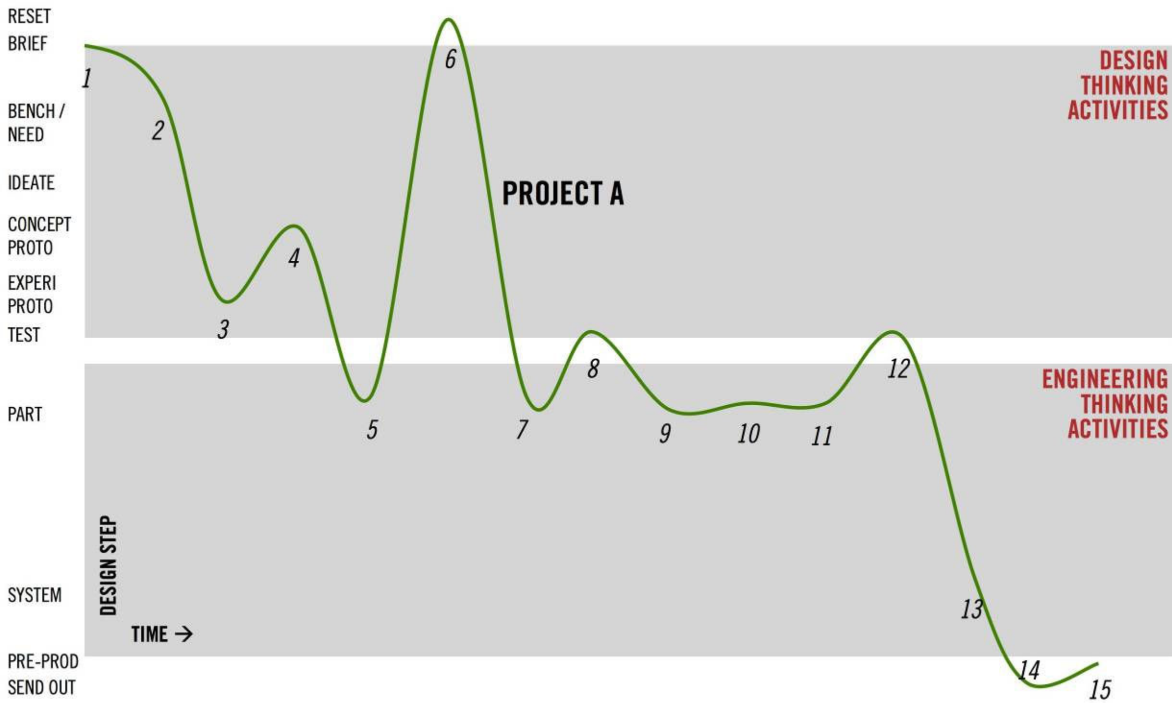

Figure 9. Map of prototyping activities for Project A.

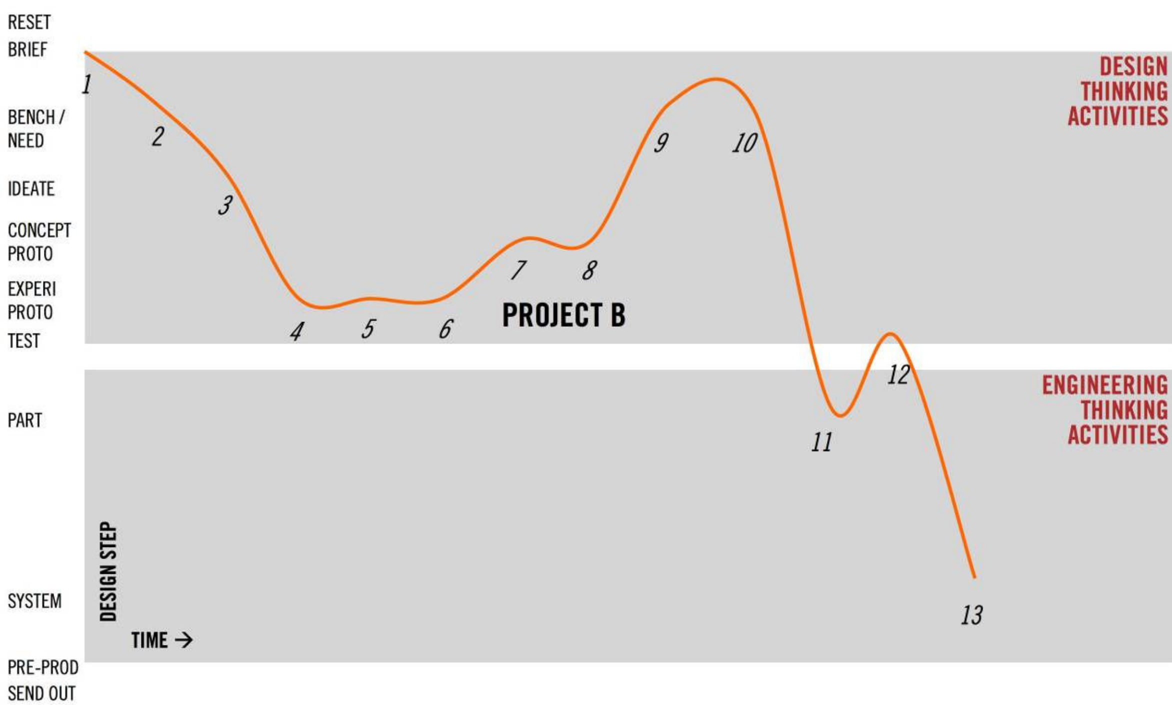

Figure 10. Map of prototyping activities for Project B.

Towards an Ambidextrous Way of Thinking

Characterizations of prototyping activities further classify design process steps. Projects with similar starting points (amorphous future, engineering optimization, etc.) were paired, coded and compared. Initial analysis shows compelling distinctions between both the subsequent pathway and resulting project space. For example, as listed in Table 4, the number of mode switches between design thinking and engineering thinking for one project (for Project A, an car company on the car copilot of 2020) was twice that of a project for a consumer device company (Project B, on very human technology) and 3x the number of unique design step activities. It is this *Ambidextrous Way of Thinking*, jumping across rather than within boundaries that seems to aid students' learning. Future work will explore this further.

BOUNDARY AREA	PROJECT A	PROJECT B
FUTURE - DESIGN	3	1
DESIGN - ENGINEERING	7	3
ENGINEERING - PRODUCTION	2	0

Table 4. Summary of jumps between design steps during prototyping activities for Project A and Project B.

These may be creative jumps between Design Thinking and Engineering Thinking activities. And it could be evidence that a co-evolution of the project and solution results in more novel solutions and better learning. Future work will bear this out. This is in line with previous work on novices and experts designer engineers [14] jumping around among design process steps.

Contrasting Foci

From observations of student engineers in Mechanical Engineering 310 we can list the contrasting foci that is paired with each Design Thinking and Engineering Thinking, summarized in Figure 5. These are priorities that shift due to whatever step in the design process the team may be at.

DESIGN THINKING ACTIVITIES		ENGINEERING THINKING ACTIVITIES
FUNCTIONAL	::	PHYSICAL
AMBIGUITY	::	UNCERTAINTY
PARADIGMATIC	::	PARAMETRIC
BREAKTHROUGH	::	INCREMENTAL

Table 5. Contrasting foci for Design Thinking and Engineering Thinking activities.

For example, the ambiguity with which projects are defined is something that students find unsettling and most certainly are not used to. As engineers, they have been trained to eliminate ambiguity, not preserve it, and to minimize any existent uncertainties. For the most part, student's work and graduate careers have been framed in closed-end problem solving. So there is a balancing[16] between preserving ambiguity and eliminating uncertainty, as shown in Figure 11, that is difficult for students to manage. The Design Thinking activities value ambiguity whereas the Engineering Thinking activities don't worry so much about the existence of ambiguity but rather the elimination of uncertainties.

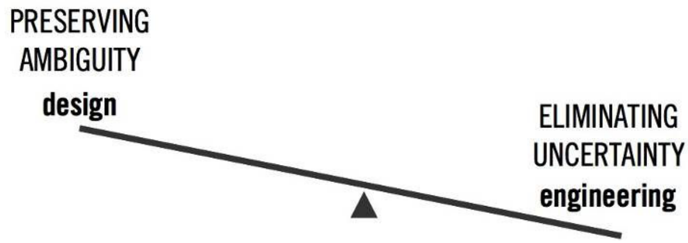

Figure 11. Visualization of balancing ambiguity and uncertainty.

Catalysts for Design Learning

With observations of student teams several emergent themes have arisen as supports and barriers to the students successfully adapting a design thinking and prototyping culture. As evidenced in field observations, noting team prototyping activities, and sitting in on regular consultation meetings teams have with faculty and teaching assistants, students are hindered by a predisposition to plan and calculate repeatedly before taking action. These students trained as engineers also have a hard time at first stepping out of the mechanical systems boundary and including a user in the system or having a user-centered design approach.

These observations have revealed some catalysts for student learning. They are facilitated by a *situative zeitgeist* – a close proximity to other groups in a shared design loft, *scaffolded prototyping* – a series of front-loaded prototype milestone assignments, *cognitive iteration* – a practice of encouraging reflection on what is gained from prototyping, and *cognitive apprenticeship* – learning aided by repeatedly stepping through the steps of the design process. These practices and local customs help the students' learning experience. Future work will explore this further by describing specific episodes of these phenomena.

Conclusions

The transition of mechanical engineer to capable design thinker is an interesting transformation. On the whole students begin the Mechanical Engineering 310 course with routine design practice. While experiencing the scaffolded prototyping activities and cognitive iterations of stepping through their design processes students start to adapt to a more iterative representation and arrive by the end of the course a more adaptive and iterative model. Neeley [16] described this as adaptive design expertise. Future work will go toward exploring how this change captures the student's cognitive development of their understanding of the design process longitudinally and suggests a learning trajectory and assessment tool for design learning along ascending representation of mental models of design.

Nominally the learning goal of the course is to teach a design process to engineering students. It's a capstone-plus [8], product-based learning experience. Most students have had a capstone design course experience [17 18] from their undergraduate studies, and some [19] have claimed the ME310 course experience can more approximate industry practice.

In ME 310, students learn judgment. They travel from designing by routine habit to designing by adaptive practice. Student transform from I-shaped people with content knowledge in mechanical engineering to T-shaped people who can be the majordomo for any multi-disciplinary collaboration once they arrive in industry. They become flexible and adroit at applying their skills, content knowledge and their judgment. They can come to ambidextrously move between Design Thinking and Engineering Thinking.

Acknowledgements

The authors gratefully acknowledge the work of students and teachers of ME310, past and present. This work was supported by the HPI-Stanford Design Thinking Research Program.

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