DESIGNING AND ENGINEERING:
AMBIDEXTROUS MINDSETS FOR INNOVATION

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FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

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NOVEMBER 2012

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ABSTRACT

Design transforms people and the stuff they make. How technical engineers learn and advance a human-centered design approach, and what catalysts and barriers for their learning exist, will be illustrated with research done with student mechanical engineering designers engaged in work practice. *Ambidextrous Mindsets for Innovation* is a framework for relating *designerly* ways of knowing-doing-acting and *engineering* ways of knowing-doing-acting. Empirical findings are based on evidence collected from nine engineering design teams in a graduate mechanical engineering course. The focus is on their prototyping habits over time, supported by observations of team meetings and review of team documentation reports.

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CHAPTER 1

INTRODUCTION

BACKGROUND AND CONTEXT

Innovation is a difficult challenge. Today, it often takes many players from many areas working together to create something new. Multidisciplinary perspectives of engineering, business and design stitched together (Feland, Cockayne et al. 2004), as illustrated in Figure 1, can achieve design innovation. This can be present in cross-

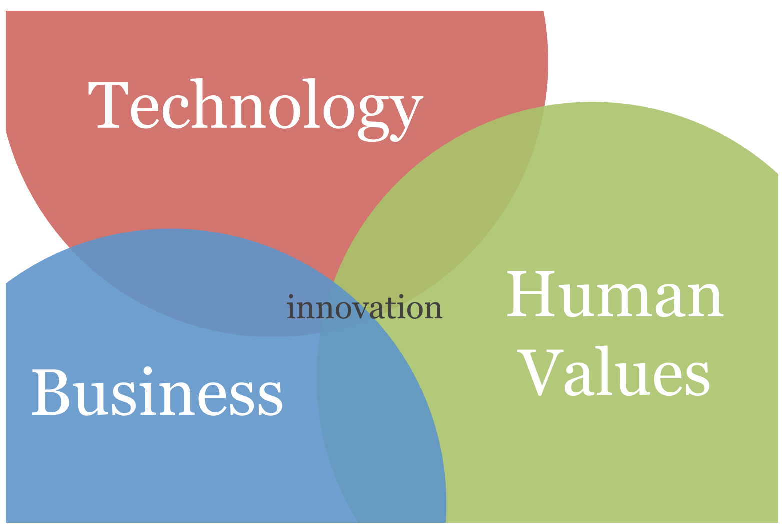

Figure 1. A comprehensive design engineering model for innovation (from Feland, Cockayne et al. 2004)

functional teams (Schar 2011) within an established organizational culture as well as in the *T-shaped* individual with depth in one disciplinary field and breadth across others (Kelley and Littman 2005). Along the way, competing voices and values often surface from groups and individuals based on their disciplinary and epistemic roots.

Design thinking has become increasingly popular parlance in the engineering design community as well as in design education (Dym, Agogino et al. 2005) and business circles (Kelley and Littman 2001; Nussbaum 2004; Brown 2005; Kelley and Littman 2005; Brown 2008; Brown 2009; Martin 2009). This design thinking approach has become useful as a differentiator for schools (Nussbaum 2009) and companies (Borden, Breen et al. 2008). For many, this human-centered design approach results in innovative and novel outcomes, sometimes leading to market success. To focus on the resulting product, service or experience, however, is oftentimes a near-sighted approach; it neglects the process, the people involved and their pathways towards a realized and refined solution. The commercial and tangible outputs of engineering design can be evident by sales (Feland 2005) or industry awards (Petersen 2010). For the underlying steps by which a product or service was created, however, not much foundational understanding exists about how these outcomes are delivered, i.e., the actual engineering design process by which such innovation is created. More importantly, there is also limited knowledge or experience in how to coach productive teams (Reich, Ullmann et al. 2009) to arrive at innovative and impactful solutions.

Examples of success by design pervade, often in the form of Apple as an exemplar of innovative products (Thomke and Feinberg 2009) or people (Isaacson 2011). Less has been captured of how these designed objects come to be other than anecdotes relating to management decisions (Levy 2011).

Snapshots of design activity (Cross, Dorst et al. 1992; Lloyd, McDonnell et al. 2007; McDonnell and Lloyd 2009) and lab experiments (Atman, Chimka et al. 1999) are present but capture segmented moments through necessarily artificial design task constructs.

The notion that problems and solutions ought to be tackled in tandem can benefit from more exploration. How does one come up with ideas and what steps are necessary to implement them? What does this evolution of imagining and making look like and how does it affect the problem and solution space? This research will study different approaches to the process of innovation and design implementation undertaken by student engineering teams. Facets of design thinking (Dym, Agogino et al. 2005) and engineering rhetoric (Robinson 1998) have been examined separately. Ideas are both important to problem formulation and problem solution.

Mindfulness of one's design process and design steps within it are areas of relatively recent concern (Carroll, Goldman et al. 2010; Meinel and Leifer 2011). The human-computer interaction community has been notable in its awareness, study and designing of tools for intervention (Klemmer 2003; Hartmann, Klemmer et al. 2005). Engineering education has used design activities with the study of design cognition (Adams 2001; Adams, Turns et al. 2003; Atman, Turns et al. 2003; Atman, Cardella et al. 2005; Atman, Adams et al. 2007). In the *Engineer of 2020* (National Academy of Engineering 2004) and the National Academy of Engineering Grand Challenges (Perry 2008), the role of design is even more important. With the general criteria for undergraduate engineering programs (ABET Commission 2010), student outcomes address topics (teaming, communication, contextual concerns) that are largely left to the providence of project engineering design courses. Engineering-focused colleges like Olin, Harvey Mudd and interdisciplinary graduate centers within schools of engineering like the Segal Design Institute at Northwestern University and the Hasso Plattner Institute of Design (the *d.school*) at Stanford University have championed project-based learning within their curriculum and become thought leaders for this sort of design education.

PROBLEM STATEMENT

Design is a discourse whose application has an evident outcome that creates a value proposition, however, the activities of those engaged in it from concept to the fruition of implementation are not well documented. How do designers and engineers do what they do, and how do they learn from such activities?

The main purpose of this study is to identify the strategies designers and engineers use as well as how those approaches are refined through experiences.

STATEMENT OF PURPOSE AND RESEARCH QUESTIONS

This qualitative ethnographic study explores the design and engineering activities of 36 students involved in nine student engineering design teams over the course of three quarters and 30 weeks. The research aim is to better understand their design and engineering experience through the patterns of design steps. In that way, the manner by which students are instructed and coached can be improved. This work can also better inform the evaluation of engineering student's design practice.

The first research question of this study is <u>how do engineering students *navigate* among their design and engineering activities?</u> A secondary question is <u>what are the catalysts and barriers to *navigating*?</u>

RATIONALE AND SIGNIFICANCE

The rationale for this study comes from the researcher's desire to uncover ways to help students with the ambiguous nature of an open-ended engineering design process. It is hoped that this descriptive work can be used as a basis for future study and result in interventions to discover more details about design and engineering activities as well as the design learning process itself.

THE RESEARCHER

The researcher was a student in the Mechanical Engineering Design Group at Stanford University and has been both a student and teaching assistant in the course under examination. Academic degrees include an undergraduate major in Engineering (Product Design) and a Master's degree in Education (Learning Design). The researcher's interests are focused on the processes and habits of the student cohort being studied. The researcher is more interested in the process than the product of the ME310 course.

The researcher was indeed biased by familiarity with the instructional approach being examined. Familiarity with the habits, activities and traditions of the course may have affected the perceptions during observation. As such, efforts have been made to rely heavily on what students have said, written and built themselves during the natural course of their practice.

ASSUMPTIONS

Based on prior experience and background as a student, teaching assistant and instructor in design courses, there are some assumptions and biases that are brought to bear by the researcher through the observations made. Familiarity with the ME310 course assignments and the ebb and flow of the course may have hidden general peculiarities about design and engineering. Local student teams worked daily with academic teams at global partner sites. However, those global teammates were not observed at a distance and it is assumed that students' weekly reports to the teaching team of the course and quarterly documentation captured the remote team's activities as well. The global students were observed when they were collocated during the first week and final weeks of the course. The methods employed throughout the year are assumed to have given sufficient background knowledge, particularly when combined with the student self-reporting in their documentation at the end of each term, to reach significant analysis and conclusions regarding their design experience and progression.

RESEARCH APPROACH

With approval of Stanford University's Institutional Review Board, the experiences of participants engaged in coursework of Mechanical Engineering 310 Project-Based Engineering Design, Innovation & Development course during one recent academic year at Stanford University were studied. The cohort consisted of 36 students grouped into nine design teams. This investigation is an ethnographic study using qualitative research methods. Prototyping artifacts created and regular design team meetings were used to document the student teams' experiences and to map their engineering design process.

Observations of weekly engineering design team *small group meetings* with the instructors and teaching assistants were the primary method of data collection. These meetings served as weekly check-ins, recitation of activities and ongoing issues, and show-and-tell of artifacts made during the project. The small group meetings were an established part of the course design. In quarterly reports (at the end of fall, winter and spring terms), students self-reported and documented their activities. The reports included a *design development* section recounting the students' prior design practice, as well as additional written documentation that provided reflection (Schön 1983; Adams, Turns et al. 2003; Currano, Steinert et al. 2012). Daily photographic records of team workspaces taken by the researcher also helped to capture project design development and place work along a timeline.

A variety of research evidence was collected to triangulate data. In addition, a comprehensive review of relevant literature and pilot studies shaped and refined the data-collection methods used. Coding categories for design and engineering activities were developed guided by the study's conceptual framework. In addition, various strategies were employed, including inter-rater reliability in the coding process, and peer review at different stages as the study progressed.

PROTOTYPING PATHWAYS & AMBIDEXTROUS MINDSETS

This work illustrates student engineering design teams' activities by capturing the prototyping pathways. An example pathway, visualized for the "mobile work" project is shown below in Figure 2. The representation highlights the *designerly* prototyping activities and *engineering* prototyping activities and the pattern alternating between them.

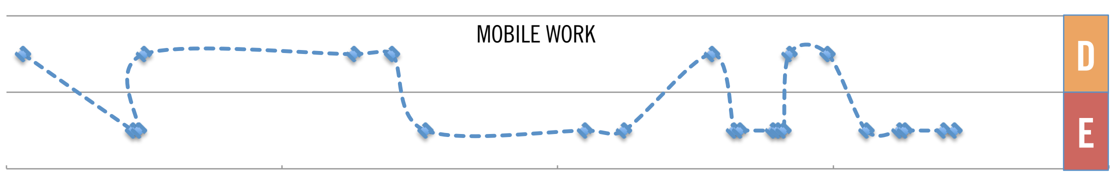

Figure 2. Example prototyping pathway for one project

Observations of student engineering design team practice and their prototyping stream and analysis of their activities help shape the "ways of thinking" framework *Ambidextrous Mindsets for Innovation*, shown in Figure 3, and further explored in this work.

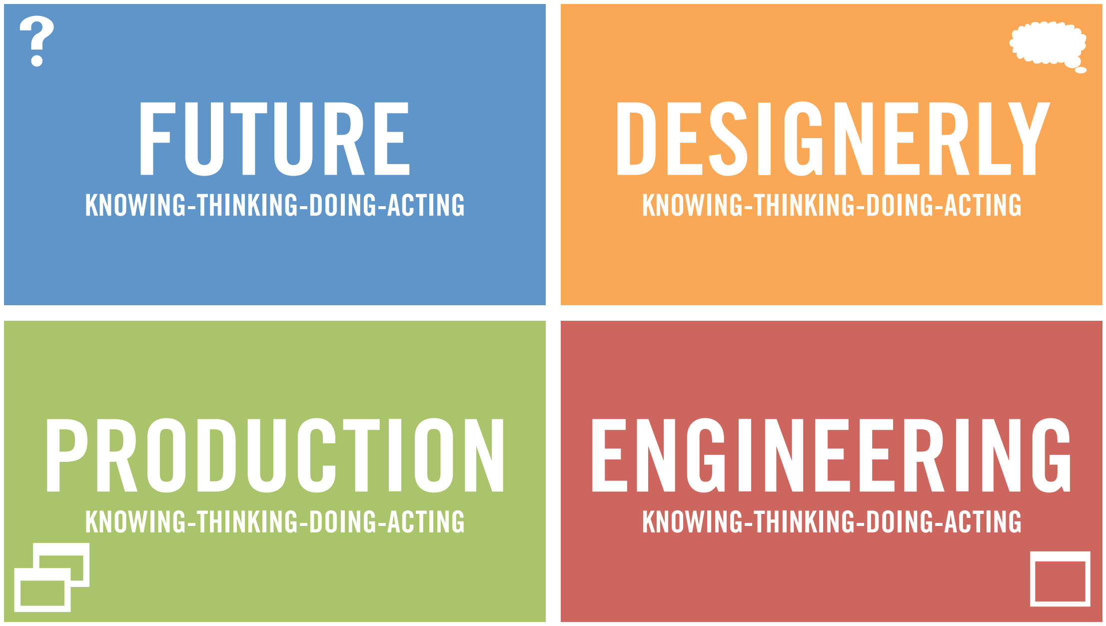

Figure 3. *Ambidextrous Mindsets for Innovation* framework

ORGANIZATION

This dissertation has eight chapters including this one. As a guide to the organization of the remainder of this dissertation:

Chapter 2 reviews relevant literature on designing and engineering, prototyping and systems of thinking.

Chapter 3 presents the methods undertaken.

Chapter 4 presents a pair of pilot studies used to inform the coding scheme used to classify prototyping activities.

Chapter 5 presents themes that serve as catalysts and barriers for students' and student teams march towards innovation. Students self-reflections are used as evidence.

Chapter 6 presents analysis of Prototyping Pathways.

Chapter 7 presents a synthesis and explores the *Ambidextrous Mindsets for Innovation* framework.

Chapter 8 summarizes the work with conclusions, recommendations and suggestions for future work.

CHAPTER 2

LITERATURE REVIEW

The purpose of this qualitative ethnographic study was to explore the design and engineering activities of student engineering design teams. The bodies of literature reviewed encompass (a) definitions for design and engineering, (b) prototyping within engineering and (c) disciplinary discourse and systems of thinking.

DESIGNING AND ENGINEERING

Humanity has been designing and engineering artifacts much longer than there has been language to describe such activity. Designers and Engineers are labels adopted in the last century to describe specialized practice performed by professionals engaged in industry. Such connotations are readily used but their precise meanings shift, dependent on context and discipline. We are concerned herein particularly with characterizing a distinction within the field of mechanical engineering, specifically where these labels may also be thought of descriptively as design engineering and engineering design.

Historic Traditions

Development and education of designers and engineers has been the province of different disciplinary traditions. The jobs of engineers grew out of war-building and civil infrastructure building. Designers have emerged from either a science-based methods focus or an arts-based tradition (Klinker and Alexis 2009). The collision of these two roles emanates from the contrast between manufacturing and commerce, the rise of material technology (like plastics to make unorthodox shapes), and computer-supported collaborative practice.

Lewin (1979) made the case for applying a systems-thinking approach to engineering practice that integrated applied design considerations. He proposed that holistic thinking through design can be more valuable than analytical thinking that could be segmented and decontextualized

Labels

Design and Engineering are labels for individuals and groups that undertake the acts of designing and engineering. Daly, Adams, et al. (2012) explored tenets of design activity that are displayed in professional fields as far afield as dance to baking to electrical engineering. For purposes of this research, the focus will be on what discourse exists relevant to engineering, engineering design and mechanical engineering design. Design and Engineering are sometimes used interchangeably or singularly distinct but have not yet been compared and contrasted.

Design as More Than Problem Solving

Cross (1982) described *designerly ways of knowing, doing and acting* with user empathy at its core. Empathy has been invoked as core to user-centered design (Norman and Draper 1986; Faste 1987; Patnaik and Becker 1999; Norman 2002; Laurel 2003; Suri and Howard 2006; Patnaik and Mortensen 2009). Dym, Agogino et al. (2005) summarized design thinking by describing core aspects as divergent and convergent (Eris 2004), about the design of systems (involving uncertainty and estimation) (Stacey and Eckert 2003; Cardella 2007; Cardella and Lande 2007; Carleton, Cockayne et al. 2008; Cardella 2010), design decisions, and as aspects of team-based activity (Tang and Leifer 1988; Baya and Leifer 1994; Brereton 1999; Leifer, Culpepper et al. 2004; Sonalkar, Jung et al. 2010; Lande, Sonalkar et al. 2012).

Problem solving has often been a part of the proffered definition for design actions but it is often only part of a larger context. Gasson (2007) enumerated design as 1) problem setting, 2) problem solving, 3) situated learning and 4) functional analysis. Cross (1995) is inclusive about engineering design activities going after ill-defined problems. Visser (2006) combined problem solving and ill-defined problems to equate to more than problem solving alone. Thomas and Carroll (1979) called design a problem approach unique to other forms of problem solving. Some also commented that design cannot be comprehended as problem solving (Stolterman 1992; Winograd, Bennett et al. 1996) or is a richer concept than problem solving (Nelson and Stolterman 2003).

Engineering has been described as a rhetoric strategy for problem solving and implementation (Robinson 1998) invoking specific language for discourse (Bucciarelli 2009) and mathematical thinking (Cardella 2007).

Specialized Roles

New engineers face *siloed* work environments where roles are specialized and responsibilities are shared across large organizations (Schar and Lande 2012). No one person works on a complete project – start to finish. There are many barriers to discourse within the manager-employee structure and dynamic (Brunhaver, Korte et al. 2010).

Capstone Engineering Design Education

Design is often taught as a series of rigid tools, methods and processes to help do engineering problem solving. Design is sometimes used as a gateway to engineering content knowledge and often used as the structure for senior engineering capstone courses (Todd, Magleby et al. 1995). Capstone design courses include engineers who are asked to synthesize their prior engineering content knowledge. Their engineering challenge is often a system that focuses on the technology and absent the people aspect of the system.

Project Based Learning (Prince and Felder 2006) focuses pedagogical efforts on open-ended, authentic problem solving. The bases of many capstone engineering design courses are engineering challenges done on behalf of a third-party, either as a sponsor or end-user.

Studies of Design Activities

Previous studies (Atman 2005, Atman 2003) have characterized the relative design processes of college students in their freshman and senior years, design educators and practicing designers. Based on individuals constrained (both by time and scope of problem) in a lab design activity, Atman et al. (2005, 2003) were able to identify and describe differences in design process practice, namely, time on problem definition, chronology of process, and iterative steps.

Additional work (Adams 2001) explicitly captures the design steps and processes of Atman's design experiments, expressly highlighting iteration as behavior of experts.

ME310 Research Basis

For researchers at the Center for Design Research (CDR) at Stanford University, ME310 Project-Based Engineering Design, Innovation & Development has long been a laboratory and test bed for design research (Ju, Neeley & Leifer 2007). Considerable attention has been devoted to how designers design, how they engage in teams and tools that can help along the way. Forerunners of ME310 (also labeled ME210, E210, E310) date back to at least 1972 (Carleton and Leifer 2009). CDR was established in 1985 and research in ME310 has been going on nearly 25 years (Ju, Ionescu et al. 2004). The ME310 class has been the research basis for studying engineering design students and their team interactions.

PROTOTYPING IN ENGINEERING AND DESIGN

Prototyping is an activity core to designing and engineering, though prototyping is an activity that has traditionally been under examined. Prototypes have been looked at as content (Lloyd and Snelders 2003) and conduct (Schrage 1996) but not through the lenses of students' learning practice in situ.

Developing a habit of prototyping early and often and continuously throughout the engineering design process is an approach used throughout mechanical engineering and design. An underlying part of a *prototyping culture* (Schrage 1996) includes both developing practices for using conceptual and experience prototyping to explore possible solution space as a means to communicate ideas and receive feedback. This process relies on iterative physical prototyping as a means to learn and further refine concepts (Buxton and Buxton 2007).

For a number of engineers in industry and academia a prototype is solely the culmination and resulting artifact of the engineering design process. Within the Express-Test-Cycle process model (McKim 1972) to the engineering design process there is a community that relies on the production of a physical or tangible artifact towards evidence of learning. Iterations of prototypes are commonplace both in the early part of the design process to disambiguate among possible solution concepts and in the latter part of the design process to reduce uncertainties about the engineered implementations of a solution. Prototyping has been described as a communication tool (Brandt 2007) and a means to answer questions (Schrage 1996) between designers, but also between designers and others.

Prototypes as Units of Analysis

Houde and Hill (1997) identified four types of prototypes, each with an associated use: role (purpose), look and feel (experience), implementation (physical), and integration (system), shown in Figure 4. Nielsen (1989) described three different types of prototypes along a scale of features of services and functionality of features. Horizontal prototypes were those with shallow functionality but wide features of service. Vertical prototypes were of narrow features but deep in functionality. Scenarios overlapped the two with only a sliver of features and functionality. Nielsen’s model was applied to human-computer interaction applications and is shown in Figure 5.

Examples of prototyping are listed in Table 1, aligned with the types of prototyping described by Houde and Hill (1997) and Nielsen (1989). This research attempts to further classify and describe these examples.

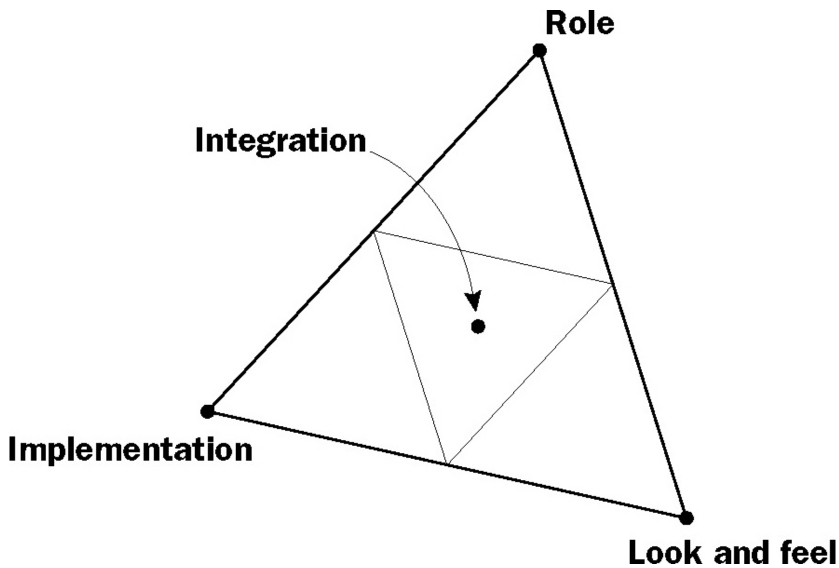

Figure 4. Houde and Hill's four types of prototypes

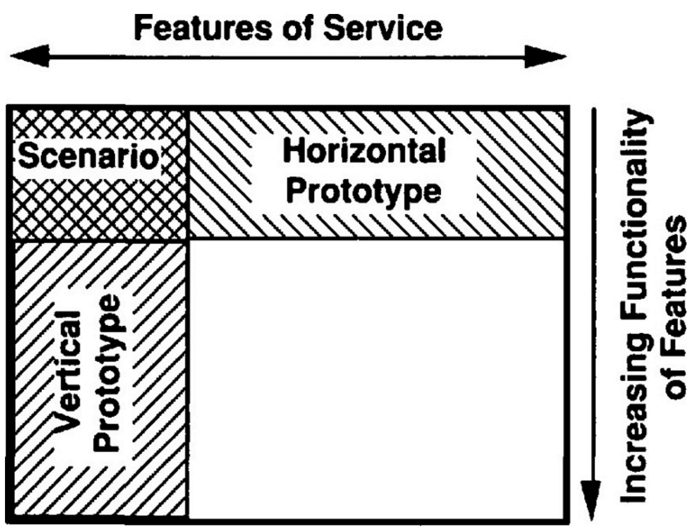

Figure 5. Nielsen's three types of prototyping

Conceptual Prototyping

Taking an idea from concept to enabling its reality in the form of a non-functioning mockup allows interaction and discourse not easily achieved with ideas presented verbally or written recorded as a brainstorm or expressed visually as sketches. These prototypes are often made quickly with materials available in the space, i.e. bricolage or making a collage with materials (Louridas 1999).

Experience Prototyping

Experience prototyping can consist of putting oneself in the place of the targeted user (Buchenau and Suri 2000; Coughlan, Suri et al. 2007). Experience prototyping can also include using conceptual prototypes in scenarios to illustrate a prototype of the experience, either within the design team or by engaging prototypical users to assess the experience. There is usually limited or no functionality on display. A willing suspense of disbelief is necessary. At this point in the engineering design process the ambiguity of the presented idea embodied in the prototype and the opening up of the problem space can be helpful in fostering more and better ideas upon which to iterate.

After ideas are evaluated, a narrowing of possible solutions occurs and the characterizations of prototyping activities do, in fact, change. While iteration may take the design team back to the earlier stages of the design process to clarify or troubleshoot, much of the continued efforts in the engineering design process refine and specify the final design.

Functional Part and System

The language of engineering prototyping is much more precise than that of its design prototyping corollaries. For example, in the detailed design phase informal sketches are replaced by specific CAD drawings and rendering.

Focused functional sub-systems that examine the physicality or mechanisms of only a part of the engineered system, vital to the viability of the solution, can be called critical function prototypes.

Houde's (1997) integration is substantiated by student *funky* (course-specific parlance for less refined, bricolage-type prototypes) and functional system prototypes. They are attempts to pull together the parts of the system, first in an efficient and possibly unrefined way (funky) and then something suitable for display to others in more of a pre-production prototype (functional).

Table 1. Categories of prototyping

Examples demonstrated in ME310 course	Sketches Benchmarking existing Conceptual prototyping Experience prototyping	CAD Critical function prototyping Functional system prototyping
Houde and Hill (1997) taxonomy	Role Look and Feel	Implementation Integration
Nielsen (1989) taxonomy	Horizontal	Vertical

Developing a Taxonomy for Describing Prototyping Activities

Previous research has described general steps in the design process. With practical limitations due to time, scope and the time a total design process takes, much of that work, in engineering education and design research, has focused on what activities may happen primarily in the early design phases, such as project scoping, the generation of alternatives, and idea selection. Atman and Bursic (1996) looked at seven design textbooks and synthesized a consensus list of steps in the design process. It is more descriptive of early design stages; implementation is left to its own general step. Crawley, Malmqvist et al. (2007) also use implement to describe the engineering space in the Conceive-Design-Implement-Operate model. These are listed in Table 2.

Table 2. Selected past efforts to define steps in a design process

(Crawley, Malmqvist et al. 2007)	(Atman and Bursic 1996)
Conceive Design Implement Operate	Definition Identify need Gather info Modeling Feasibility Evaluation Decision Implementation

DISCIPLINARY APPROACHES

C.P. Snow (1961) bisected the fields of humanities and sciences. Calling out the deficit in discourse between these two cultures in modern times, Snow regarded the division between the humanities and the sciences as contributing to barriers to collaborating and finding solutions to societal ills. With the computing and second technological revolution, the field and culture of engineering has widened the canyon to include another gap.

A multiplicity of perspectives and stakeholders make successful collaboration difficult. Considering the values and priorities that exist within each field's viewpoint, such asynchronous intersections can be expected. Examinations of interdisciplinary collaborations (Borrego 2006) described more difficulties faced within closer fields than across dissimilar academic fields. A disciplinary range from hard-to-soft or pure-to-applied arises because the *knowledge fields and cognitive communities* (Becher 1994) that do (close) or do not (far) share overlapping language with alternative meanings are liable to make communication more confusing. It is the lack of *clarity and conciseness in the lexicon* within and beyond the field of mechanical engineering (Messac and Chen 2000) that inhibits cooperation within and collaboration across disciplines.

Balancing Depth and Breadth

Calls come for future innovators who are *T-shaped* (Kelley and Littman 2005); that is, having both a deep, abiding knowledge in one discipline (electrical engineering or anthropology, for example) and having breadth, through knowledge, skills or practice, to be able to collaborate across disciplines. The character of the innovator's design acuity or shared language enables one to connect across the silos of their main disciplines, engaging well with others (Brown 2009).

The Stanford School of Engineering repeats this balance of breadth and depth with its pedagogical exhortation in the Undergraduate Engineering Handbook (Stanford 2010) with regards to curriculum requirements for engineering science classes as *Engineering Fundamentals*.

Historical Context

In the 15^{th} Century, collaboration was much simpler. Vocations of individuals (cobbler, blacksmith) allowed for efficacy and oversight of the creation of artifacts and technology. *Renaissance men,* like the archetype Leonardo da Vinci, could conceivably be knowledgeable about many aspects of their life, science and technology of their day. In 1800s England at the precipice of the Industrial Revolution, for another example, the Lunar Society of Birmingham (Uglow 2006) demonstrated that a small cadre of learned polymaths could be influential – such as pottery manufacturer and entrepreneur Josiah Wedgwood and steam engine-inventor James Watt. The Founding Fathers of the United States of America like Thomas Jefferson and Benjamin Franklin can be considered in this same mold.

Systems of Thinking

Professor John Arnold migrated to Palo Alto from MIT in the late 1950s. Collections of writings for creativity workshops at the time described *Creative Engineering* (Arnold 1956; Pandora 2006) in which a wider context of understanding was suggested to solve problems. This was in parallel with Buckminster Fuller's concept of a Comprehensive Anticipatory Design Science, part of his brand of *Dymaxion* thinking (Sonalkar 2007).

Building on Fuller's call for the philosopher-artist-scientist, Feland, Cockayne et al. (2004) summarized IDEO's Innovation Engine (Weiss 2002) and the tripartite of effective design (technology, business and human issues) (Asimow 1962) into a model of design innovation consisting of feasibility, viability and usability. A permutation of this proposed setup for teaching innovation has become a conceptual basis for the multidisciplinary design teams: engineers, business and design.

On the individual level, holding or alternating among multiple perceptual fields or acuities has been labeled as *Hybrid Thinking* (Patnaik and Mortensen 2009) and moving among convergent and divergent actions as *Pivot Thinking* (Schar 2011).

Mandate for Innovative Approaches

There is local value in breakthrough thinking (Stefik and Stefik 2004) over incremental thinking. This may be a regional bias near the Silicon Valley but others have made cases for innovative approaches to educating future engineers. The National Academies of Engineering's *Engineer of 2020* (National Academy of Engineering 2004) makes the case for a reinvention of engineering education, as do Sheppard, Macatangay et al. (2008) and Duderstadt (2009), pushing towards contextual inquiry and authentic problem solving as part of the engineering curriculum. Concerns over persistence in engineering and understanding students' pathways in and out of, and through their undergraduate engineering education, have also been the subject of collaborative research (Atman, Sheppard et al. 2010).

CONCEPTUAL FRAMEWORK

The conceptual framework is based upon constructivism. It is the notion that one can discern thinking via that which is being created and that one creates knowledge by doing (Piaget 1950). It encompasses a hands-on project-based learning pedagogy (Prince and Felder 2006) found within much engineering design coursework.

SUMMARY

This work is informed by areas of literature demonstrated by (a) definitions for design and engineering, (b) prototyping within engineering and (c) disciplinary discourse and systems of thinking in engineering design. This qualitative ethnographic study explores the design and engineering activities of student engineering design teams. The context is the ME310 Project-Based Engineering Design, Innovation & Development course at Stanford University, a research basis used previously by others exploring phenomena around professional engineering design teams.

CHAPTER 3

METHODS

The purpose of this study was to explore the activities of student engineering design teams. Their learning experience can be improved by better understanding the pattern of their design steps, the way they are instructed, and the role of coaching. The first research question of this study is how do engineering students *navigate* among their design and engineering activities? A secondary question is what are the catalysts and barriers to *navigating*?

OVERVIEW OF RESEARCH DESIGN

In situ observations of student engineers doing design was undertaken in the academic year 2008-2009. This was done in weekly student team meetings as well as in a weekly class section (Leydens, Moskal et al. 2004). Documentation analysis (Leydens, Moskal et al. 2004) was done of student reports that were generated at the end of fall, winter, and spring quarters (every 10 weeks). Review of previous year's student documentation was also undertaken to help illustrate and support findings.

The teams of mechanical engineering graduate students were observed during regular team meetings and their project reports analyzed. The researcher sat in on weekly team meetings and class presentations, gathering qualitative notes *in situ* in written notebooks. Audio recordings were also made but were not transcribed or reviewed. Interim project reports detailing the design development of their activities as well as the final specifications of all their projects were analyzed and a coding scheme using these student-reported reflections was used to map the students' experience, activities and design process steps.

Team and individual reflections within their documentation reports were also captured and categorized. Selected student reflections appear in Chapter 4 as evidence of some emergent themes about students' relationships with their engineering design process and prototyping.

RATIONALE FOR QUALITATIVE RESEARCH DESIGN

Qualitative research is based on constructivism (Piaget 1967), seeking to better understand and situate complexity in a broader context (Guba and Lincoln 1998). With activities of student engineering design teams, the intent is to collect a *holistic* understanding over a *reductionist* understanding (Schwandt 2000). The main objectives of this methodology are to gain meaning from (student) experiences (Bogdan and Biklen 2007). The researcher is purposefully not engaging quantitative research methods and is not seeking to test hypotheses. The qualitative research methods employed allow for gathering rich data needed to develop contextual and interpretive understanding.

RATIONALE FOR ETHNOGRAPHIC STUDY METHODOLOGY

Within a qualitative approach, the study was suited for an applied ethnographic study design (Chambers 2000). Ethnography is a methodology conceived to collect thick descriptions of human activity in real-world scenarios. In this case, it is the real world of student engineering design teams' activity in a graduate level curriculum at a leading research university. By observing team meetings, field notes were captured with regard to the discussions at hand, the interactions of team, instructors and teaching assistants (Leydens, Moskal et al. 2004), as well as the artifacts, context and minutiae of the shared design space, or project "loft."

THE RESEARCH SAMPLE

Individual students enrolled in a Master's level mechanical engineering design and innovation course were included in the sample cohort. The criteria for selection of participants was: (a) participants were enrolled in the same Master's level mechanical engineering design and innovation course (ME310), (b) participants were co-located at the local campus (i.e., not part of the global cohort) and (c) participants had given permission to be included in the study.

The research sample included 36 individuals who were starting the Master's in mechanical engineering program during the 2008-2009 academic year. Students were organized in teams engaged in one of nine projects within the course, as coordinated and selected by the course instructors. Table 3 lists the nine engineering design projects.

Table 3. Topics tackled by student engineering design teams

Generalized project label	*Sponsoring company or organization*
Alternative fuel car adoption	Environmental venture capital co.
Building design	CAD software co.
Dental care	Consumer electronics co.
Falling down safe	Government safety advocacy group
Flexible work force	Software service co.
Mobile health monitoring	Phone utility co.
3D sensing & measuring	Industrial tool-tech co
Vehicle-Human 2020	Car co.
Wearable friendship	Consumer electronics co.

The course Mechanical Engineering 310 *Global Team-Based Design Innovation with Corporate Partners* is a core mechanical engineering and design product-based-learning (Prince and Felder 2006) course sequence for first-year Master's students in mechanical engineering. It features student teams collaborating on corporate sponsored authentic industry design projects. Each academic year, the course features approximately 8-12 projects with student teams and corporate sponsors. Over time, the engineering design project briefs submitted by sponsoring companies have evolved from manufacturing, testing, and assessment equipment to more product focused problems. In recent years, problems that industry has presented focus less on traditional mechanical engineering or mechanical design systems problems, but rather focus more on general *wicked* (Rittel and Webber 1973) and *ill-defined* problems (Buchanan 1992).

The basic pedagogical approach is comparable to the iterative ideal design process model (Adams 2001; Leifer and Meinel 2011), as evidenced by course assignments and milestones to teaching design in ME310. Through coaching (Reich, Ullmann, Van der Loos & Leifer 2009), students are asked to adopt an arguably more advanced and mature model of design as they adapt to the deliverables of the class. Along the way students encounter conceptual blocks with problem setting and re-setting (Bucciarelli 1994), fixation on ideas (Jansson and Smith 1991) and solution focusing (Lloyd and Scott 1994). These and other phenomena were captured and analyzed as emerging themes from studied design activities by way of situated qualitative design observation.

ME310 is a "capstone-plus" course. Rather than having a learning goal of synthesizing everything in the students' engineering content knowledge as a capstone experience, it requires applying judgment to solving problems. It is more about what should be done rather than what can be done. Graduate mechanical engineering students begin the course sequence as engineers and end up thinking about themselves as designers (Lande and Leifer 2009). As listed in Table 4, students come into their first year of the Master's program in Mechanical Engineering having received their requisite undergraduate education in mechanical engineering or a related field.

Table 4. Student demographics in study

Number of students	36 9 female, 27 male
Undergraduate degrees	32 mechanical engineering 2 bioengineering 1 aerospace engineering 1 humanities & sciences
Co-terminal students	9

A small number of Stanford students continue from their undergraduate studies directly into this course through a co-terminal program. For most, their exposure to design, design thinking, and the design process has been limited to a discrete capstone engineering course or exposure to design in industry during internships, if at all.

The course sequence is structured to give student teams both the time and freedom to explore their problem-solution space within a safe environment from which they learn how to step through a design process. Weekly meetings take place with the course faculty and teaching assistants. Teams also have a local coach from industry to help them progress. Well-defined course milestones are geared towards early hands-on prototyping and students are strongly encouraged to collaborate locally within their design team as well as with their global design team members.

Nominally the learning goal of the course is to introduce a design process to engineering students. The Mechanical Engineering 310 course experience has been described as approximating industry practice (Skogstad and Leifer 2011).

The learning objectives of the course are to have students 1) produce a preproduction proof of concept prototype of a refined solution from a given prompt, 2) be able to develop and evaluate engineering requirements, 3) foster team building and teamwork skills, and 4) develop individual skills such as project management and planning (Lande and Leifer 2010).

Team performance assessment is heavily weighted on documentation produced throughout the academic year. These documents and oral presentations are treated as evidence of the students' thinking and learning. A 100-200 page final report is generated by each team in the spring and includes descriptions of the design problem, requirements, design development and specifications for the end solution. Fall and winter draft reports serve as precursors to the final spring documentation.

Student teams have project funds of $10,000-20,000 and oftentimes outsource part of the fabrication or finish of their end design. The expectation is that the final engineered deliverable be a pre-production prototype – a proof of concept that functions as desired, including consideration of potential manufacture.

ETHICAL CONSIDERATIONS

Participation was voluntary and informed consent was obtained, adhering to approved human subjects protocols via the Stanford University Institutional Review Board. Students were engaged in their engineering design coursework. Efforts were made to not disturb or annoy the participants and the researcher made efforts to separate activities from those of the instructors and teaching assistants who were responsible for the course grading.

Student privacy was maintained. Photographs taken to document the use of space excluded faces. In preparation of the data for analysis, generic descriptors of projects were used, listed in Table 3 (on page 23).

ISSUES OF TRUSTWORTHINESS

Multiple lines of evidence were used to do data triangulation (Denzin 1978). By using multiple sources (student self-reports, meeting observations, photo journaling), data can be supported from multiple perspectives (Leydens, Moskal et al. 2004). These efforts were key to support credibility, dependability, confirmability and transferability (comparable to validity and reliability in quantitative research methods) (Guba 1998).

LIMITATIONS OF THE STUDY

The researcher was mindful to represent himself as a researcher, in a role separate from that of the instructors and teaching assistants that made up the teaching team. Students were informed of the nature and intent of the research at the start of the course. This was part of the informed consent protocol, included in Appendix. During observations, small group meeting sessions were regularly attended by the researcher. The researcher was careful to sit on the outside of the assembled group and not interject. Occasionally, students inquired about what field notes were being written down; the researcher duly informed them that its purpose was to capture the discussion and conversations. When engaged, the aim was to be cursory yet polite with students and explain the research interests plainly and generally. On a very small number of occasions (approximately 10 over 30 weeks, or 1 per 20 hours of observation) when a member of the teaching team wanted to share a reference or point to a previous project but was unable to remember specifics, and the researcher could, such information was volunteered. The researcher was mindful of the role of observer and limited direct interactions with students while observing their meetings. As the course progressed there was interaction with students outside of their formal meeting times to inquire about their activities and progress, but as a researcher only and not involved in their course grading.

DATA COLLECTION METHODS

Qualitative research methods were used to analyze 200+ hours of observed team meetings and 27 design reports (Leydens, Moskal et al. 2004). Data sources included:

1. observations, in weekly engineering design team meetings
2. photo record, from daily photographic records of activity in design spaces
3. artifacts and prototypes, created by design teams throughout the course
4. quarterly reports, end-of-quarter engineering design team documentation
5. individual student reflections, on process in team documentation

Surveys were circulated asking about student perceptions and conceptions of engineering and design (Lande and Leifer 2009) but were not part of this analysis.

SUMMARY

The design and engineering activities of student engineering design teams were observed, captured and analyzed. In the context of the ME310 *Project-Based Engineering Design, Innovation & Development* course sequence, a qualitative research design was undertaken to explore (1) <u>how do engineering students *navigate* their design and engineering activities?</u> and (2) <u>what are the catalysts and barriers to *navigating*?</u>

CHAPTER 4

PILOT STUDIES

Initial research efforts explored the nature of projects undertaken in specific graduate engineering design and innovation course. These pilot studies informed the structure, focus and findings of the main study. A better understanding of the types of projects over time was gained. A means to classify project types and initial efforts to apply that coding scheme outlined in Chapter 3 to prototypes was explored.

TYPES OF PROJECTS OVER TIME

The yearly slate of projects offered in ME310 is wholly dependent on companies from industry proposing and underwriting project proposals. A dedicated course developer solicits and manages the process. Faculty and staff help edit project prompts for scope and appropriateness to the course pedagogy. Student teams are presented with the array of possible topics, rank their choices and are then assigned a project in a *satisficing* (Simon 1969; Simon 1972) approach.

For a mechanical engineering course, understandably, much of what is produced is a physical, tangible artifact. There are oftentimes components or whole sub-systems that are not designed mechanically but rather include software or mechatronics. Mabogunje (1998) examined the class set of ME310 projects in the 1991-1992 and 1992-1993 course cycles. He was able to define three types of projects: manufacturing process driven machine design, product driven machine design, and a hybrid of the two, a mixed product and process driven machine design. Historically, this designation is able to capture the distribution of project types. With a rise in a user-centered design approach, industry seeking design to solve a wider range of problems and more future-oriented projects, new types are required. A new category of projects needs to be introduced that goes past system optimization and system design, to take into account the presence of a user engaged in the designed system. Therefore, it is necessary to add the category of *user-centered design system projects* on top of those that deal mostly with manufacturing process, testing and tools for assessment and standalone products. Additionally, more projects have come with suggested briefs that encompass more than traditional mechanical engineering topics. There has been a rise in human-centered projects and, interestingly, projects scoped to be 5 to 10 to 20 years out into the future (Saffo 2007; Carleton and Leifer 2009; Shedletsky, Campbell et al. 2009).

CLASSIFYING PROJECTS

To better classify projects it is also useful to add a characteristic descriptor to indicate the project type. A type can be assigned to each project according to its project content focus at the beginning or end of the project or at any point within the project (from amorphous to specific). The classification scheme used for determining the project content focus (Lande and Leifer 2009) can be represented along the following distinctions, shown in Figure 6:

- Amorphous Future
- Specific Future
- Amorphous Design
- Specific Design
- Engineering Technology
- Engineering Optimizing
- Production Technology
- Production Optimizing

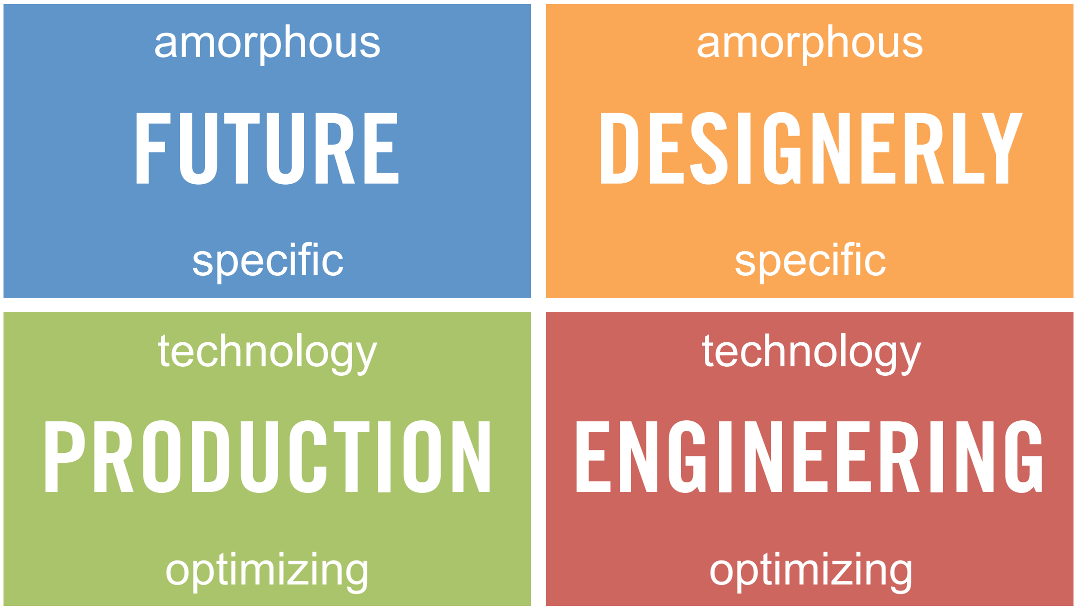

Figure 6. Array of project content categories

Table 5 lists projects from selected past years. The share of projects has shifted over the years (Lande and Leifer 2009). Manufacturing-focused projects have become less common and user-centered Design projects more so. Tool-focused projects have also declined while Product-focused projects have grown slightly and fluctuated in recent years. Projects from 1979 have a lot of manufacturing projects with their terms and project titles like *low cost* or *high speed* as well as measurement projects like *Arm Ergometer* and *Design Steam Leak Measurement*. Projects selected from 1999 still mostly fall into *Product* projects. As examples there are systems that involve people like *Smart Bed* and *Car Door* projects. More recently, projects from 2009 show a user-centered design approach and a number of *Product-* and user-centered *Design*-focused projects that ask students to look into the future for the solution space or technology solutions.

Table 5. Example project topics from selected years

1979	*1999*	*2009*
Arm ergometer Design steam leak measurement system High-speed Kevlar wrapper Low-cost facsimile printer Robotic arm controller Universal gas seal	Driver scanning automatic car door Innovative composite clutch Inspection device for contaminated blades Key fob Parallel parking assistive system Power expendable towing mirror Shift simulator Smart bed	Alternative fuel car adoption Building design Dental care Falling down safe Flexible work force Mobile health monitoring 3D sensing & measuring Vehicle-Human 2020 Wearable friendship

APPLICATIONS FOR CLASSIFICATIONS

This survey classification of past projects is helpful to get at the gross trends over a number of years. It is instructive and informative to see patterns in the focus of project prompts from industry for student practice.

Being more mindful of the evolving types of projects pursued is helpful. This is tempered by both the awareness and concern that established pedagogies for Manufacturing-focused projects is different than for Product-focused and user-centered Design-focused projects.

Questions also arise regarding the students' steps through the design process. Is the process different for projects of different types and in what ways? This question is left unaddressed here. A pilot exploration has captured where ME310 projects end up but, in this analysis, the company prompt and where the student teams have taken the projects is not matched. A next step is to examine more closely more complete records from sets of projects to understand the relationship between the prompt and end product.

It is useful to define and characterize such variables as the types of projects posed in courses like ME310 in order to be more explicit and reasonable about the expectations from the student, faculty and industry sponsor perspectives.

DOCUMENTATION PILOT STUDY

A pair of student projects from a prior academic year has 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, as shown in Figure 7 and Figure 8.

Analysis of Prototyping Activities

From field observations, photo records, artifacts and prototypes and quarterly reports, maps of prototyping activities were gathered. An *a priori* coding scheme was developed to describe such prototyping activities. These (conceptual and experience prototyping, functional part and functional system prototyping) are listed in Table 6, organized around *designerly* and *engineering* prototyping activities.

Table 6. A priori coding scheme for team prototyping activities

Future Thinking Activities Resetting	*Design Thinking Activities* Benchmarking Needfinding Ideating Conceptual prototyping Experience prototyping Testing
Production Thinking Activities Sending Out	*Engineering Thinking Activities* Functional part prototyping Full system prototyping Pre-production prototyping

These classifications of prototypes, as well as the basis for these descriptive terms and the use of prototypes as units of analysis, are discussed earlier in Chapter 2 Literature Review. This coding scheme for prototyping activities is also applied to pilot study analysis for student projects A and B described in Chapter 4.

Capturing Design Steps

By analyzing student documentation, it is feasible to capture the design steps that the student teams undertook. Table 7 lists the content focus of the prototyping activities undertaken by each respective team.

Table 7. Prototyping activities captured for Projects A and B

Project A design steps	*Project B design steps*
1. BRIEF *Nebulous Copilot*	1. BRIEF *Very Human Technology*
2. BENCHMARK	2. NEED *Interactions*
3. EXPERIENCE *feature manager*	3. IDEATE
4. IDEATE *co-communicator*	4. EXPERIENCE *shared environments*
5. FUNCTIONAL PART *info organizer*	5. EXPERIENCE *desirable screen*
6. RESET *information processor*	6. EXPERIENCE *form factor*
7. FUNCTIONAL PART *info organizer*	7. CONCEPTUAL *storyboarding*
8. EXPERIENCE-TEST *buttons, feedback*	8. CONCEPTUAL *mobile commenting*
9. FUNCTIONAL PART *audio alert*	9. BENCHMARK *wireless*
10. FUNCTIONAL PART *AV output*	10. BENCHMARK *RFID tags*
11. FUNCTIONAL PART *generic voices*	11. PART *table pc with interface*
12. TEST	12. EXPERIENCE *looks like*
13. FUNCTIONAL SYS *vibrating buttons*	13. FUNCTIONAL *works like*
14. SEND OUT *fabrication*	
15. PRE-PRODUCTION PROTOTYPE	

Visualizing Design Steps

Figure 7 and Figure 8 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, then worked towards the goal of having a preproduction prototype at the end of the course, even outsourcing some of the fabrication of parts.

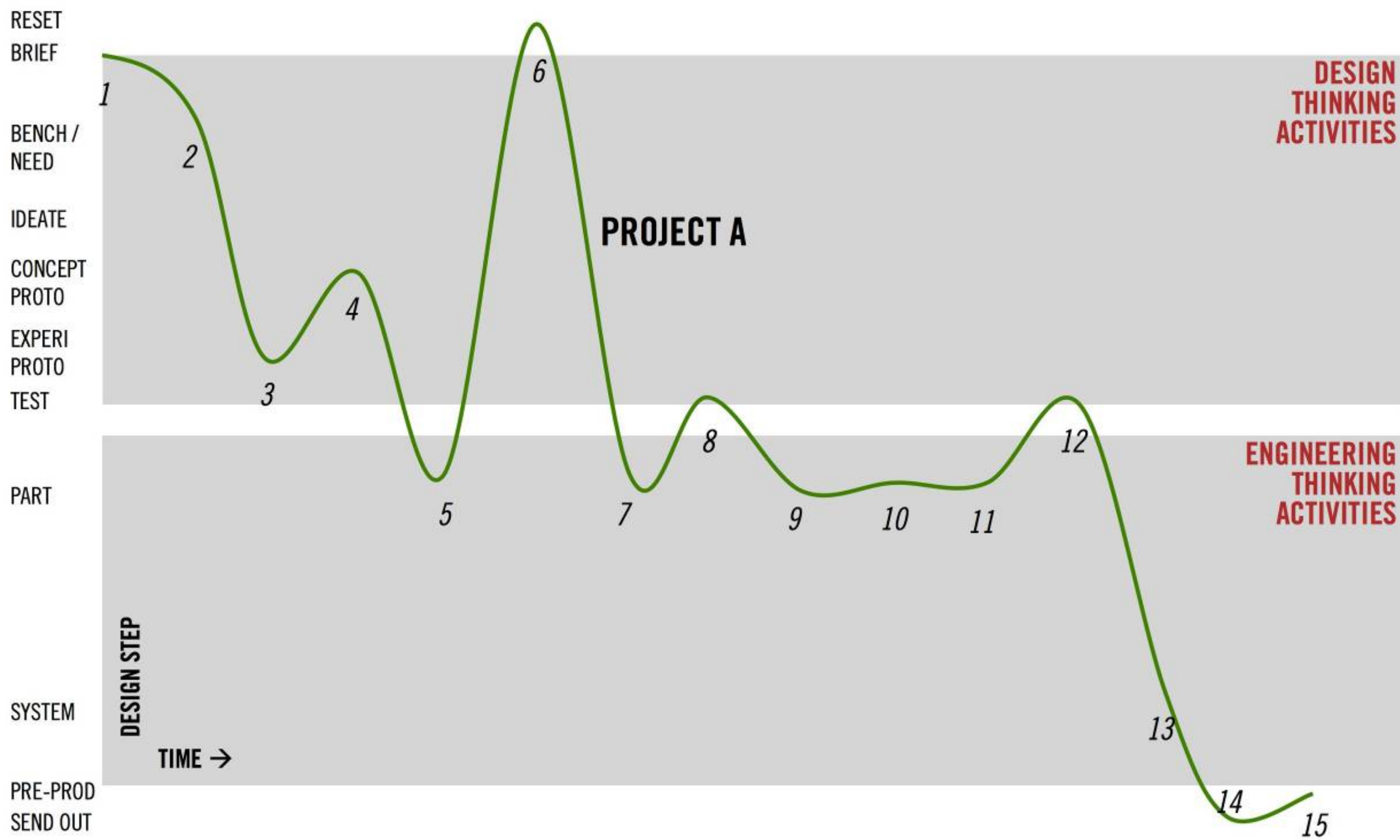

Figure 7. Map of prototyping activities for Project A

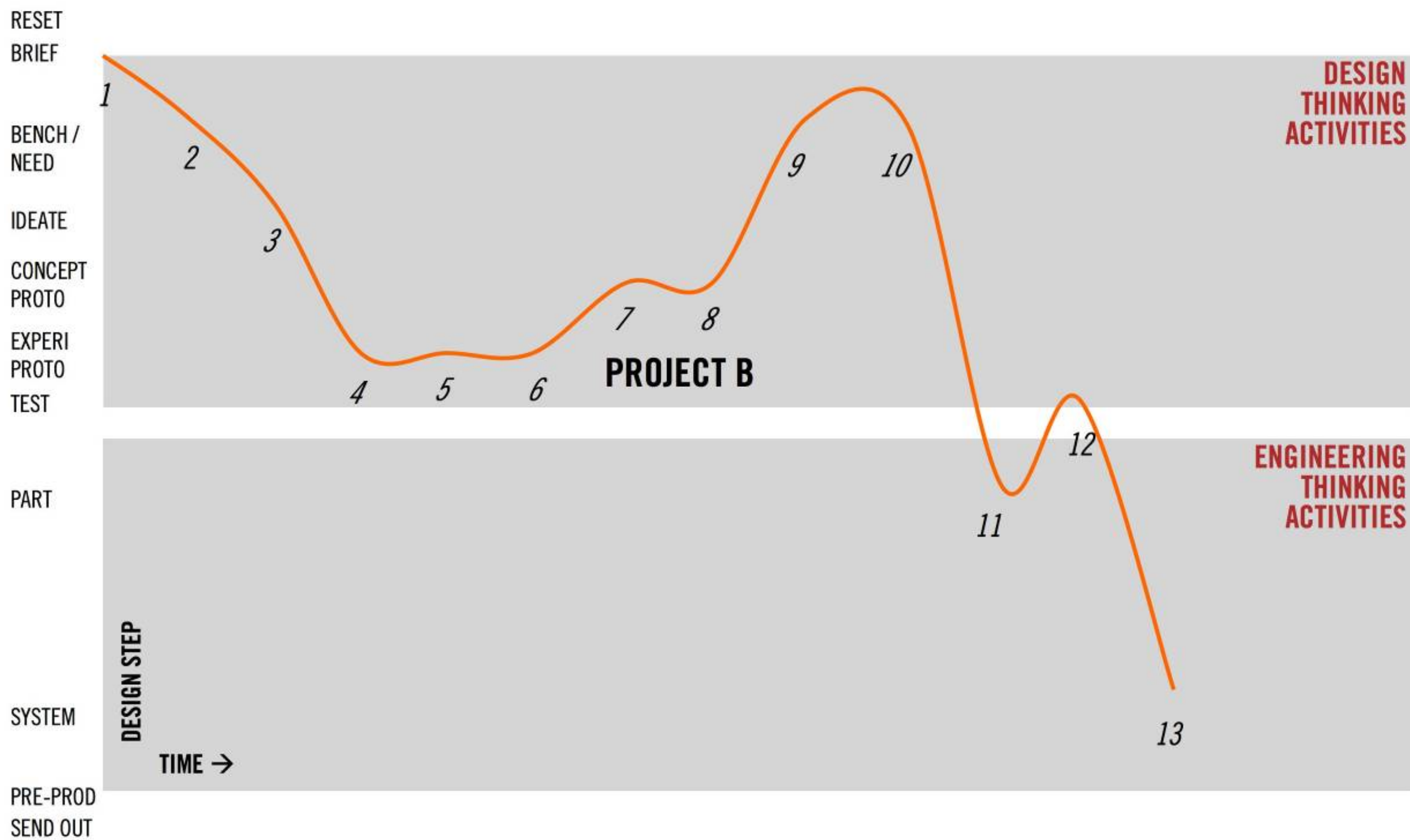

Figure 8. Map of prototyping activities for Project B

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 process 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 to take their ideas and their design experiences out of the realm of just Design Thinking into Engineering Thinking and having physical tangible artifacts. Their activities stopped short though of having a preproduction prototype. However, their end result was a directional wayfinding 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.

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 8, the number of mode switches between design thinking and engineering thinking for one project (for Project A, the car copilot of 2020) was twice that of a project for a consumer device company (Project B, on very human technology) and three times the number of unique design step activities. It is this *Ambidextrous Mindsets*, jumping <u>across</u> rather than <u>within</u> boundaries that can aid students' project advancement and learning.

Table 8. Summary of jumps between design steps during prototyping activities

Boundary area	*Project A*	*Project B*
Future / Design	3	1
Design / Engineering	7	3
Engineering / Production	2	0

The design steps evaluated in Table 8 may be creative jumps between Design Thinking and Engineering Thinking activities. Moreover, it could be evidence that a co-evolution of the project and solution results in more novel solutions and better learning. This analysis is in line with previous work on novices and expert designer engineers (Adams 2001) jumping around among design process steps.

SUMMARY

Pilot studies were helpful to explore the research questions undertaken. These efforts informed the structure, focus and findings of the main study.

CHAPTER 5

CATALYSTS AND BARRIERS

Several emergent themes have arisen as supports and barriers to the students successfully adapting a design thinking and prototyping culture based on the researcher's observations of student teams.

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 space or project "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 improve the students' learning experiences.

As evidenced in field observations, noting team prototyping activities, and sitting in on regular consultation team meetings with faculty and teaching assistants, students are hindered by a predisposition to plan and calculate repeatedly before taking action. Those 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.

CATALYSTS

Situative Zeitgeist

The course resides in a collaborative engineering design area that fosters implicit learning in a community of practice (Wenger 1998). The array of people and affordances in the space allow for close collaboration and peer support in building skills, experiences and development towards being a future engineer.

As Master's students in a core class within their design theory and methodology concentration, the shared engineering design space or project "loft" becomes a popular place to hang out, whether engaging on a project or other activities. The space becomes a learning ecology (Barron 2006) in its own right. As one student contributes, it becomes central to their experience:

> I can't wait to see next year's group of 310er's walk into the loft and have NO idea what lies ahead. They will walk in the door looking at 310 like a regular course, but be confused by the crazy contraptions hanging from the ceiling. In this crazy place called "the loft," they will learn how to really work with other people for the first time. The students will be amazed at how technically involved building a bike out of paper can be [an introductory engineering design activity]. They will read the corporate sponsor prompts, and be both excited and intimidated by the ambiguity of some of the projects. They will form teams, and try to find a balance of both talent and mutual interest with a group of individuals as talented and intelligent as them. They will learn how to rapidly prototype something, and learn that the message conveyed by the prototype is more important than the finished look of the prototype. They will learn how easy it is to become emotionally involved in a project, and will learn how to manage these emotions so that they are always constructive to the project. They will learn how to 'embrace ambiguity,' and they will learn how some of the best ideas for the project come out with a little (lot) of [brandy] and a late night in Finland. They will learn to leverage the technical skill of each member of the team, and that anything imaginable can be made in the loft. They will spend late nights, and come to think of getting to bed by 3am as an early night. They will learn that [video conference room] is actually a really nice space to sleep, and that the design group office has some damn good coffee. They will experience the reward and excitement of EXPE [year-end project fair] on no sleep, and be more proud of their project than almost anything else that they have ever been a part of. And, lastly, they will feel a deep nostalgia as the year comes to a close.
>
> [Quote 1]

Another student quantifies those long hours,

> I think success was inevitable, provided most of us put our all in to whatever it is we decided on. And that is exactly what we did. 100hr weeks for a month straight? At least one person in the loft [from our team] from 7:30am till 2am almost every day?
>
> [Quote 2]

Students in the Mechanical Engineering 310 course, regardless of their particular project, have some difficulties in approaching and managing their design projects. The constellation of the course affords a strong support structure. Students collaborate in teams of 3-4 students locally at Stanford and are matched up with similar teams of students at globally distributed university partner sites. They are provided with a sizeable project budget and a physical collaboration space in a project "loft." Student teams also have a coach from industry to consult on technical and team dynamics issues. The team then may include formal and informal advisors (Reich, Ullmann et al. 2009) in the classroom introducing informal and formal learning loops (Eris and Leifer 2003), fostering a *community of practice* (Wenger 1998) and forging a *learning ecology* (Barron 2006) in the shared engineering design space or project "loft."

Collaborating closely together with others is also somewhat of a challenge. Students are mostly in the first year of their Master's program, in their early twenties, without project experience. Issues with project management, planning and communication are always learning experiences for student teams. One student reflects on the team experience and lists a few of the bumps along the way:

> … We were lucky. The team is effective and our efforts are often well-orchestrated (despite a lack of planning, lapses in communication, and ballooning stress levels)…
>
> [Quote 3]

Students are introduced to a human-centered design process with emphasis given to rapid prototyping and iteration. Moving from *planning* to *doing* so rapidly is often a dramatic switch in the student's usual practice.

The environment and the people help form strong bonds. The experience has been likened to a start-up environment. A student reflected on that aspect as well:

Students are introduced to a human-centered design process with emphasis given to rapid prototyping and iteration. Moving from <u>planning</u> to <u>doing</u> so rapidly is often a dramatic switch in the student's usual practice.

The environment and the people help form strong bonds. The experience has been likened to a start-up environment. A student reflected on that aspect as well:

> After completing my undergrad degree I wasn't quite ready to go to the real world. I enjoyed learning, I loved [being here], and I wasn't sure if I was mentally or emotionally ready for a full time job. Well, ME310 fixed all of that in the best ways possible. It perfectly bridges the gap between school and work, functioning as an 8-person startup where you have help and guidance along the way. You make close friends, you stay up late, you wake up early, you work with awesome teammates from around the world, and you solve real problems. I couldn't have asked for a better experience. From the outsourcing to the deadlines to the project management to the travel to the budget to the personalities to the assignment to the pressure to the fun I feel like ME310 did a fantastic job of prepping me for life beyond [here], and I look forward to maintaining many of the friendships I've developed this year.
>
> [Quote 4]

And another student reiterates the job-like experience,

> For me, it has been much like working a full-time job at a typical Silicon Valley startup, sans pay and sans risk of losing your job if you fail miserably. This is the beauty of [class] to me – it allows you to take risks, to really go out on a branch with innovative ideas, without this fear of risking anything more than a hyphen behind your letter grade. It is precisely this type of environment that fosters creative design thinking and innovation that defines [this course].
>
> [Quote 5]

Scaffolded Prototyping

The ME310 pedagogical model has limited pre-defined milestones and assignments for the student teams but scaffolds in a way to encourage student team self-efficacy and independence. Assignments decrease from quarter to quarter both in number and frequency. Rather than a linear design process model, the assignments and milestones in ME310 serve to model a more expert design approach for the students.

The milestones and assignments in the course overlay the pedagogical model of ME310 over the *Ambidextrous Mindsets for Innovation* ways of thinking framework.

The class both supports iterations in the design process as well as opportunities to redefine or re-set the project or problem statement. With the pre-production prototypes deliverable at the end of the term, students are encouraged to outsource elements of the project whether it be plastic part fabrication or electromechanical control design, providing them with additional experience in communicating their work to professionals.

Prototyping to Learn

Students' reflections on their prototyping experiences in the ME310 course yielded some additional emergent themes beyond those discussed from the literature or design/engineering split mentioned above.

A Place to Start

Students found prototyping activities, of any sort, to be helpful to ground their projects and help with the project direction:

> The team felt that prototyping was the best way to bring a sense of direction for the (quarter), and that it was a necessary activity before developing a plan.
>
> [Quote 6]

> I think having a prototyping session helped everyone really focus on what they wanted out of the project. Building prototypes independently helped all of us understand what we enjoyed doing, what we wanted out of the project, and what we are good at doing.
>
> [Quote 7]

Getting Smarter

Students also commented on the scaffolded learnings gathered from their prototyping activities that helped them build on the work that they had done and get smarter along the course of the project:

> Developed from the combination of extensive benchmarking, conceptual prototyping, and user testing, this prototype presented the essential features in an integrated package. By verifying previous design concepts, the team has determined the advantageous features and areas for further refinement.
>
> [Quote 8]

> The design requirements of the project were constantly refined based on the new knowledge gained from the prototypes. This prototype was very significant as it involved testing of a new idea that was critical to the implementation of (technology) in the intended device.
>
> [Quote 9]

> Based on extensive prototyping and testing done in the winter quarter, the team demonstrated the practical feasibility of the (technology).
>
> [Quote 10]

Making Better Practice

Students found their prototyping habits to be beneficial to their practice efficiency. Prototyping also helped them be strategic about their steps and establish assessments and benchmarks to guide their activities. Some example student reflections about making better practice:

> [Team] generated numerous functional prototypes, each building upon what was learned during construction and testing of previous prototypes and through benchmarking. The change of focus early (winter quarter) and the series of prototypes made regarding (device) control, helped (team) have a clear vision of how the final product was going to look like and how it was going to be made. Some basic functions were approached with the functional prototypes, and user testing had refined the final prototype and has stemmed ideas for future improvements. [The team's] progress and narrowing focus were (helped by) two central questions asked of every prototype: 'What can we build on from this prototype?' and 'What can we discard?'
>
> [Quote 11]

> The (spring quarter) series of prototypes fall into one category, the best way to place all components of the final product together. Prior to this date, the team's prototypes sought to answer various questions, such as 'How are the… (components going to) look like?' Attempting to answer this question, the team made a series of prototypes, at first very rough and conceptual, then increasingly refined. The process of working from rough to refined prototypes saved the team a lot

> of time by not forcing them to worry about unimportant details along the way. Duct tape and hot glue proved to be especially helpful!
>
> [Quote 12]

Cognitive Apprenticeship

In the standard classroom, the role of the instructor is to be didactic and impart information to the assembled students. With the notion of cognitive apprenticeship, a master demonstrates and elaborates on his expertise for the benefit of the student. In the context of engineering design practice, the collaborative process itself serves, by proxy, in the role as teacher (Sheppard 2009). Here is one student describing his experience with the design process:

> With the traditional design process a designer is given a set of requirements and hypothesizes a perfect solution and tries to find the path that is quickest and cheapest while still meeting the requirements. The process we are being taught in this class teaches us to start with some requirements, take those requirements and do additional needfinding before design and end up at A' as a starting point. Then we take a zigzag path filled with ambiguity and prototypes, with a few honest steps toward attaining what we believe to be the best solution. But through this zigzag, ambiguous process we actually discover that a better final solution than we imagined exists.
>
> [Quote 13]

Another student reflects on what he learned:

> Now on to what I have learned. Well, an amazing amount – and just as important, I have proven to myself that I am capable of accomplishing really big things within an extremely (and almost unrealistically) accelerated development cycle. Proponents of "the process" may not want to hear this, but the biggest thing I have learned is not how to implement the design process to make a better product. Nope- the biggest lesson I will walk away from this experience with is the mentality in order to accomplish, you must DO! That might sound simplistic; but it's actually much harder than one would imagine. Don't get me wrong – it's not about doing for the sake of doing. At the end of the day, there has to be some substance behind your actions; however it IS about doing BEFORE you feel FULLY comfortable that you know everything there is to know about what it is you are doing in the first place. That is a lesson that will carry me through many difficult and ambiguous challenges far into the future.
>
> [Quote 14]

Questions of *what did you do?* and *what did you learn?* helped students reflect on their project and project directions. Oftentimes this would occur during one of the team's weekly small group meetings with the course instructors and teaching assistants. As one student describes,

> For the design team, many deadlines were discussed and based around Small Group Meetings (SGM). During these weekly meetings, the team would meet with the Teaching Team and discuss the current challenges and difficulties. Although major deadlines were set, in between these, there were many small, flexible milestones. The team found it useful to discuss these smaller, unofficial milestones during SGM. Often, this discussion would lead to a plan for the week, with the deadline being the next SGM. These meetings served as a useful tool and helped guide the team when concrete deadlines weren't set.
>
> [Quote 15]

Cognitive Iteration

For many students this is their first extended and in-depth exposure to a hands-on engineering design project. With this new course experience, students have difficulties in managing the assignments and necessary collaboration. Every team collaborates to prototype and iterate numerous design and engineering prototypes. Low cost and rapid prototyping and approach of *prototyping to learn* (Carroll, Goldman et al. 2010) pervade. Students build self-efficacies (Bandura 1977) to solving open-ended tasks:

> I learned so many things in so many areas that I never imagined mechanical engineering would entail, including soldering impossibly small components on excessively crowded PCBs, circuit components, dealing with vendors, making good looking presentations and reports, the list goes on. It has also taught me to cope with crazy intense schedules, skipped meals, and lack of sleep, and in all that keeping my sanity and learning not to be as grumpy as I could easily be when I'm hungry and tired.
>
> [Quote 16]

> I really gained confidence for the real world in my ability to do harder-core engineering tasks and figure out new ones.
>
> [Quote 17]

Students and teams are introduced to new skills, content and experiences that are also amorphously scoped:

> Only now that EXPE [year-end project fair] had come and gone do I understand and appreciate the hard work of ME310a and ME310b [quarters] where I often felt lost and frustrated. I now appreciate the brainstorming, need finding and exploration that we did because it shows strongly in our results.
>
> [Quote 18]

Teams also struggle to redefine engineering requirements appropriate to their project. A student reflects on different approaches to problem solving:

> … In traditional engineering, pure knowledge is valued much higher than a vivid imagination. Even with my background in engineering, this class has taught me to believe that the imagination is more important than knowledge, and I have surprised myself. And I have surprised myself even more when the people around me believe it too. If and when the troubles arrive, this imagination kills those problems…
>
> [Quote 19]

BARRIERS

Students dealing with ambiguous future-scoped projects have additional sets of difficulties in approaching, solving, and resolving their projects. As envisioned five to twenty years out in the future, the specificity in which their assignment is described is thereby much less specific – it is ambiguous.

Living with Ambiguity

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, a student's experiences and graduate career have been framed in closed-end problem solving. One student reflects on experiences in the ME310 course:

> … I was sometimes frustrated by a lack of order and decisiveness in the project. I often feel like we spend a lot of time discussing ideas, and have a difficult time turning the ideas into actions that we can ultimately draw conclusions from and move forward… I'm all about execution and organization, while most of the other teammates prefer to preserve ambiguity. I've been very conscientious of the need to hold back on my desire to converge our ideas into a solution during the first

quarter, and am still trying to figure out how to maintain the right balance between supporting new ideas while also making necessary decisions…

[Quote 20]

Students develop a multitude of different methods with which to cope with these difficulties. They oftentimes resolve and arrive at novel and successful project outcomes. They use up valuable time and resources in their attempts, hesitant to take chances or make mistakes.

Understanding the Problem

Future-scoped projects often have nebulous noun phrases: *car co-pilot*, *elderly care future*, *very human technology, novel interaction method.* Student teams try to understand what these could mean and ground their benchmarking of current technology on what exists today. Students have a hard time constraining their problem space and spin their wheels trying to capture everything, noted by the following student reflections:

… Our scope was from the very beginning too wide, and we should have narrowed it down a lot. Dispersing a field of ideas is a good thing – if the dispersion covers only one area. Our dispersion covered all the ideas in the world that relate to (the topic)…
… I think the situation is that we (and I) have a lot of ideas, and a sense of where to go, but due to poor [self] management we are not able to explore all the routes that we would like, or at least I would like, to explore…

[Quote 21]

Re-setting the Problem Space

Through design activity like functional benchmarking and experience prototyping, students come to re-define their project direction from the initial prompt. They may re-define the solution space to further constrain the possible solution set. As a student relates, it is not easy:

… The seemingly simple task of defining our problem was very difficult and cumbersome…
… We have come a long way from the beginning of the project, re-describing and refining the given assignment to better meet the needs on the market based on vast and thorough benchmarking…

[Quote 22]

A simple way in which students have ameliorated their own unease with an amorphous future-scoped project is to re-set (Bucciarelli 1994), change or redefine their project direction and scope.

Re-scoping the Problem Space

In contrast, re-scoping the problem opens up the problem space and expands to a broader allowance of what question the project is then attempting to address. It allows for more possible creative solutions. A student reflects on re-scoping the project due to new information from others:

> … We met a lot of people giving different inputs and wanting different things… Our team finally received the much needed inputs from (our corporate sponsor). The additional information seemed to diverge a lot from the initial requirements given to us… [Quote 23]

Paralysis of Inaction

With amorphous future projects, student teams applying a normative design process do so in a way that is inefficient and causes them to spend extra time on early design steps when compared to other types of projects. The absence of a clear path sometimes renders the student design team rudderless:

> … At times, due to the number of different paths we could have taken in developing the (project) and a lack of firm criteria according to which to prioritize what we should spend our efforts on and what to prototype, time has not been spent as effectively as it could have been. However, I suspect this is normal considering how broad our initial project brief was… [Quote 24]

As a culmination of all the frustrations of the topics listed above, as time rolls by in the course, student teams face moments of increasingly important decisions. Sometimes inactivity is the safe way to go. A student recounts such a moment in their project of being stalled by indecision:

> … progress slowed as team members were waiting if there's change in course. Indecision lasted for a week while waiting for feedback from the liaison. After a decision to proceed, …that next deadline is around the corner and lot of questions remained unanswered… [Quote 25]

Technology as a Panacea

Engineers are focused on the physical and possible. They have a techno-optimistic view of the world and stuff, technology and mechanisms are the *lingua franca* of the discipline. A cool gadget or gizmo (a Wii Remote, touch screen or a simple mechanism) is exciting and may sometimes serve as a distraction.

Technology, correctly implemented, can solve most any problem. Or so an engineer might think. Sometimes the focus of the student design team was fixated on the role a piece of technology could serve, a faith in technology:

> … Some things we have also discussed and agreed on are the need for (the component) in the future. This will be a big aspect of the project, since (the component) will be the most expensive part of our project so far. (The component) will be a great aid for prototyping…
>
> [Quote 26]

Dealing with future envisioned projects, student teams often seek out specific functionality that cannot yet be done with existing products or current technology. Because the technology might not yet be there, oftentimes a functional system can be put together with an element of the system being completely oversized (like having a computer in the trunk of a car rather than a microprocessor) or even using a *Wizard of Oz* technique (Dow, MacIntyre et al. 2005) to pull off a completely engrossing experience. A student describes dealing with voice recognition as part of a project:

> … The decision was made early during spring quarter that voice recognition software would not be used in the final prototype. An early winter quarter prototype had demonstrated that voice recognition can be used to chat in a car, but the software took over an hour to train well, and even then was unreliable and slow. In addition, the design team did not have the resources to integrate voice recognition seamlessly into the other software being developed, and our attempts to integrate the technology in the short time frame given would have led to an overly complicated and unreliable system.
>
> Because we wanted a system that could be tested by real users, and demonstrated quickly to a large number of people at the end of the year design fair, we decided to use a transcriber. The transcriber would listen to an audio feed of the driver's voice and, using a custom programmed software application… type what was being said when buttons were

> pressed. During user testing and the design fair, we took turns transcribing what was said. We affectionately came to call this role "the Wizard," a reference to the man behind the curtain in The Wizard of Oz, who makes it seem that things are happening when they are actually being faked...
>
> [Quote 27]

The Future Is Bright and Shiny

Once tasked with designing for the future, student teams often raise their expectations of how novel or innovative their solution should be. It is not for today – it is for tomorrow. They might judge their ideas more harshly or simply not think their ideas novel enough to move forward on:

> … Many of our weaknesses as a team were brought to light, namely, the ability to do original "out-of-the-box" thinking. This is something that we are constantly working on both as a team and as individuals. Now is the time to think foolishly and try crazy ideas that are impractical before we need to buckle down and start finalizing our plans—this is something that we need to embrace…
>
> … Sometimes I can be so indecisive because I want to pick what's BEST, what's perfect, what everyone will like. My team reminded me that there isn't just ONE correct solution like in a multiple choice exam; that's the thing about design…
>
> [Quote 28]

Breakthrough and Incremental Innovation

Breakthrough innovation is harder to accomplish than incremental innovation. The risks and rates of failure are greater but the rewards are greater as well. Considering concerns of sustainability, the potential and impact of design, design thinking and design engineering, it makes as much sense, if not more, to be concerned with how to design the future as minimizing the footprint of stuff on our world.

Training the next generation of student engineers to be able to develop and apply their judgment to such untenable issues seems like the best option we have.

Engineering students are hard pressed to consider *not* what could be done but, rather, what *should* be done. So what can be done to help? Programs like the Mechanical Engineering 310 course as chronicled above help. Equipping technical students with a liberal, expansive education and basis in social and economic understandings also helps.

For engineers and designers it helps to make them aware of concerns for the planet as well as the array of supports and barriers often found in student engineering practice considering re-designing the future. To be aware, engage in reflection and strategic application of design steps, be empathetic and to prototype cheaply, early and often, are all aphorisms that could help education and practice.

The hope here is that breakthrough innovation through designing the future can benefit the whole world.

SUMMARY

Student self-reflections are used to demonstrate themes of catalysts and barriers evident from field observations and prototyping activities. Table 9 lists these below.

Table 9 Summary of catalysts and barriers

Catalysts	Situative Zeitgeist Scaffolded Prototyping ▪ A Place to Start ▪ Getting Smarter ▪ Making Better Practice Cognitive Apprenticeship Cognitive Iteration
Barriers	Living with Ambiguity Understanding the Problem Re-setting the Problem Space Re-scoping the Problem Space Paralysis of Inaction Technology as a Panacea The Future is Bright and Shiny Breakthrough & Incremental Innovation

These catalysts and barriers can be mapped to the general coding scheme that is used as the basis for the *Ambidextrous Mindsets for Innovation* framework (and detailed in Table 6). The barriers described are blocks (Adams 1986) that appear at the borders between the defined quadrants. These barriers are overlaid onto the “ways of thinking" framework below in Figure 9. The catalysts are meta-strategies that support collaborative action, prototyping and reflective activity. These catalysts can be all encompassing of the engineering design process and are means to be mindful about process.

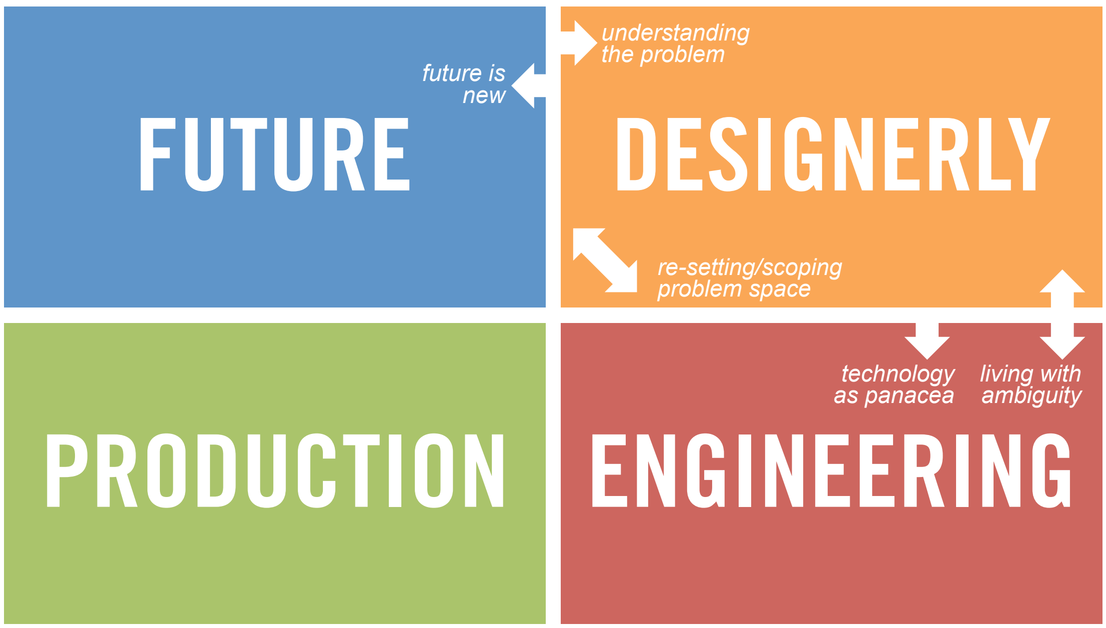

Figure 9 Barriers overlaid and mapped to the "ways of thinking" framework. *Paralysis of Inaction* not shown. Catalysts are mindful activities that encompass the engineering design process, not any one space.

CHAPTER 6

FINDINGS

The purpose of this qualitative study was to explore how engineering students navigate design and engineering activities. The student teams and their prototyping activities were observed and it is their use of and habits with prototyping that are captured in this work. The holistic context of the students' activities helps to provide context to the artifacts they created.

Specifically, this chapter will present a summary of findings with regard to the students' quantity and quality of prototyping habits demonstrated by their design and engineering activities.

JUMBLED DESIGN STEPS

Prototyping activities were captured for all nine student teams observed. These activities were plotted visually on timeline graphs crossed with the groupings of types of prototyping. Figure 10 shows an overlay of the complete set of projects over the course to demonstrate the variety and variance in how project teams advanced. Structured models of the design process exist (Pahl and Beitz 1984; Ulrich and Eppinger 1995; Cross and Cross 2000) but unstructured methods point less to routine design practice and more to adaptive design expertise (Neeley Jr 2007; Atman, Kilgore et al. 2008) models of design process (Beckman and Barry 2007). Leifer and Meinel (2011) capture a representation of design steps shared during the course with students in the ME310 design and innovation course observed, as seen in Figure 11.

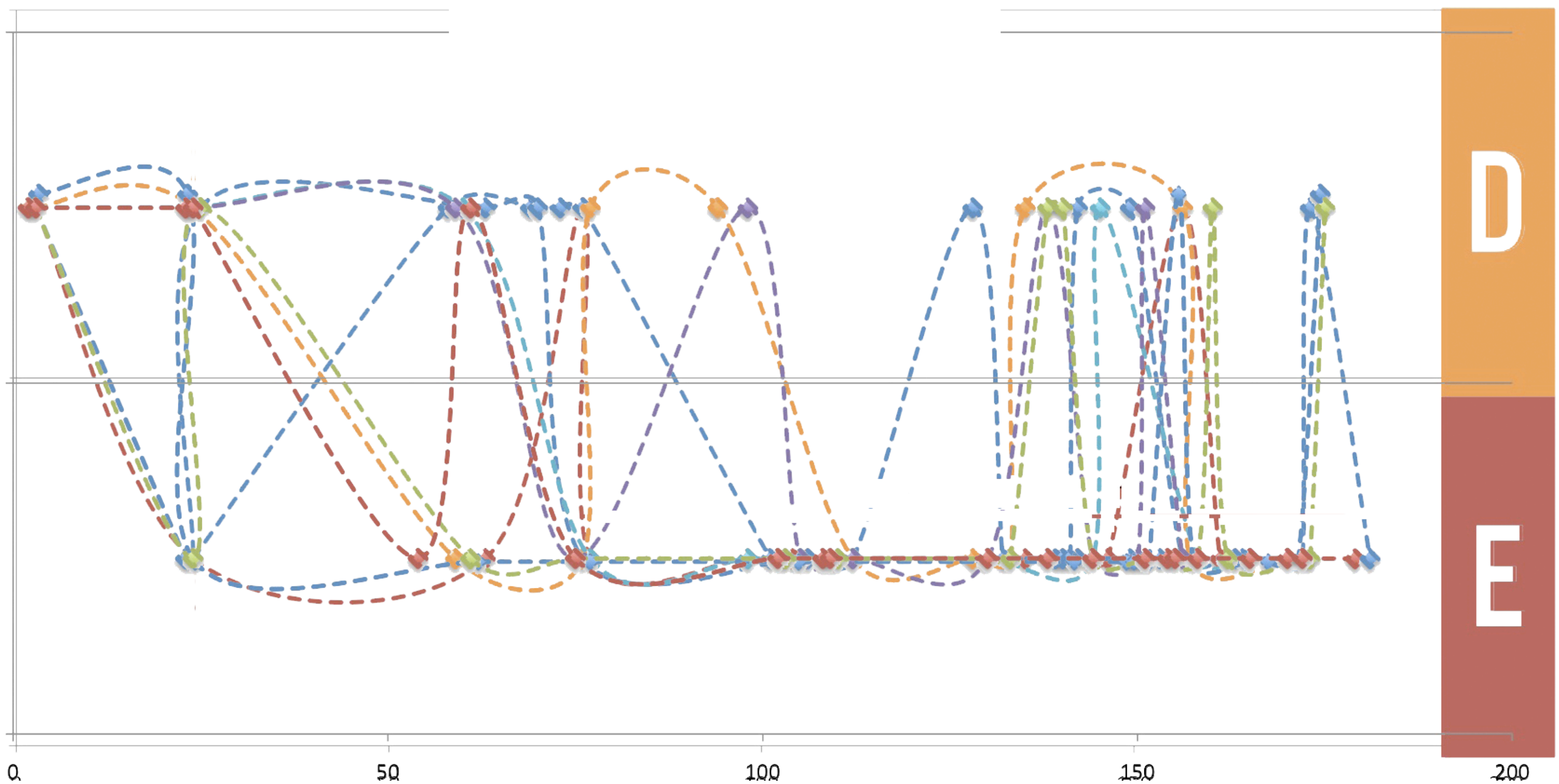

Figure 10. Overlay of prototypes created by student teams over the course.
Prototypes are grouped as conceptual and experience prototypes (mapped to a Design space, indicated with “D”) and functional part or system (mapped to an Engineering space, indicated by “E”). The timeline count is of days advanced in the course.

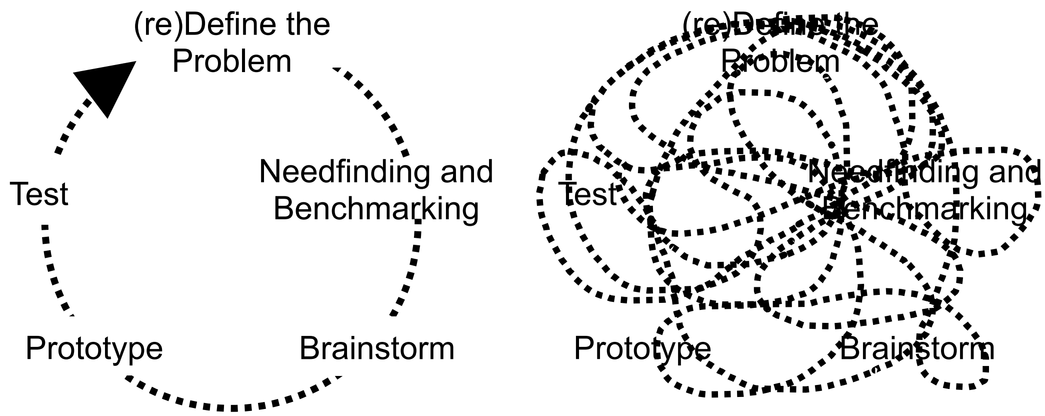

Figure 11. Example iterative design processes shared at beginning of course (from Leifer and Meinel 2011)

This is in line with Adams (Adams 2001) who looked at iterative design steps among undergraduate groups of freshmen and seniors in a laboratory experiment (Atman, Chimka et al. 1999; Atman, Cardella et al. 2005), Figure 12.

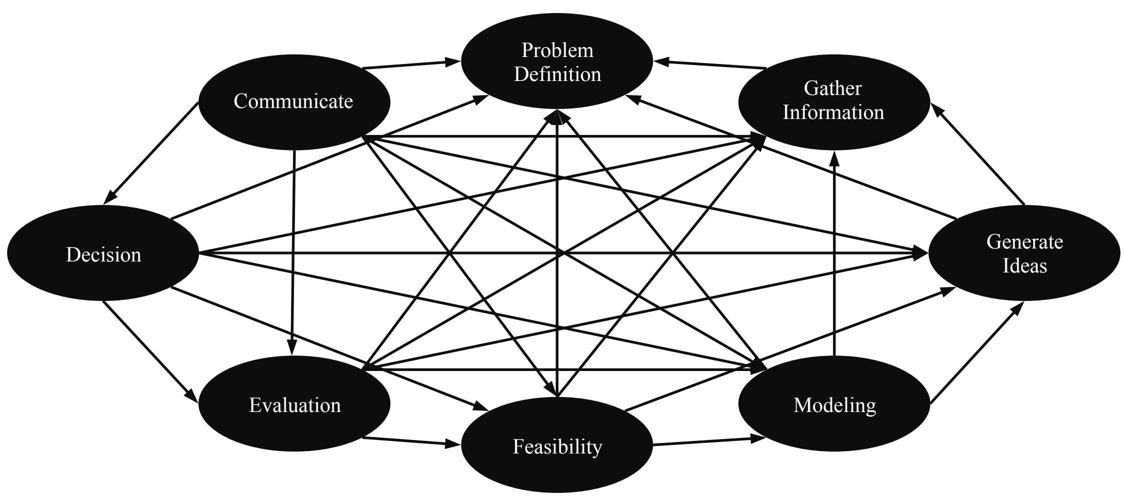

Figure 12. Map of idealized iterative links (from Adams 2011)

T-SHAPED PROTOTYPING

Student design and engineering practice and design learning is aided greatly by continued and iterative design and engineering prototyping activities, or *T-shaped* prototyping activities. *T-shaped* is meant to apply to the exploration in breadth through conceptual-functional prototyping and exploration in depth through physical engineering prototyping (see Figure 13).

Figure 13. T-shaped prototyping strategy.
Adapted from common usage (Kelley and Littman 2005) applied to people with depth in one area and breadth through design thinking to collaborate and work with others from other fields.

Prototyping is at the core of the way designers and engineers practice. This research reviews and summarizes established frameworks into the role of prototyping, and are synthesized into a new way of characterizing prototyping: design thinking and engineering thinking prototyping activities. Projects that explore both the design thinking and engineering thinking prototyping spaces benefit from cycles of converging and diverging thought, learning at each step of the process, thus nominally making for a better outcome.

Student reflections on their prototyping experiences show emerging themes of prototyping: as *a place to start*, a way towards *getting smarter*, and a means towards *making practice better*. Written reflections from students are used as supporting evidence. It is encouraging to see students and coaches of students being strategic and meta-aware of their design steps in order to best approach and guide design and engineering projects with prototyping activities and types of prototypes. Perhaps the definitions and examples of types of prototypes can aid student engineers in better finding their way through the design process. It can also help prototype to learn and learn to prototype.

EXPANSIVE VERSUS RECURSIVE PROTOTYPING

The ordering and proximity of the typology of prototyping seems to have an effect on the development of the problem and solution addressed within the space of prototyping activities. Making such a distinction is useful. Those prototypes that explored the functional space (with conceptual and experience prototypes) differed in goal from those that explored the physical (through a functional part or function system). Pivots within or pivots across those spaces can change or modify the project direction. Prototyping across, or *expansive prototyping*, helps to co-evolve the problem and solution spaces. Prototyping within, or *recursive prototyping*, helps to refine ideas or implementations further. Each is possible though one may be preferred depending on if the larger goal is breakthrough or incremental innovation. An example from one project is shown in Figure 14.

In these prototyping pathways, periods of design fixation were manifest. Sometimes it was due to refining or exploring a question, or *functional fixation* (Duncker and Lees 1945). Jansson (1991) labeled this idea fixation. Other times, due to exploring or refining an answer, or *physical fixation*. Lloyd (1994) called this solution focusing.

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, by the end of the course, arrive at a more adaptive and iterative model. Neeley (2007) described this as adaptive design expertise. Future work can go toward exploring how this change captures the student's cognitive development of understanding of the design process longitudinally. A learning trajectory and assessment tool for design learning along ascending representation of mental models of design can also be suggested (Adams, Turns et al. 2003; Lande and Leifer 2009), see Figure 28 in Chapter 6.

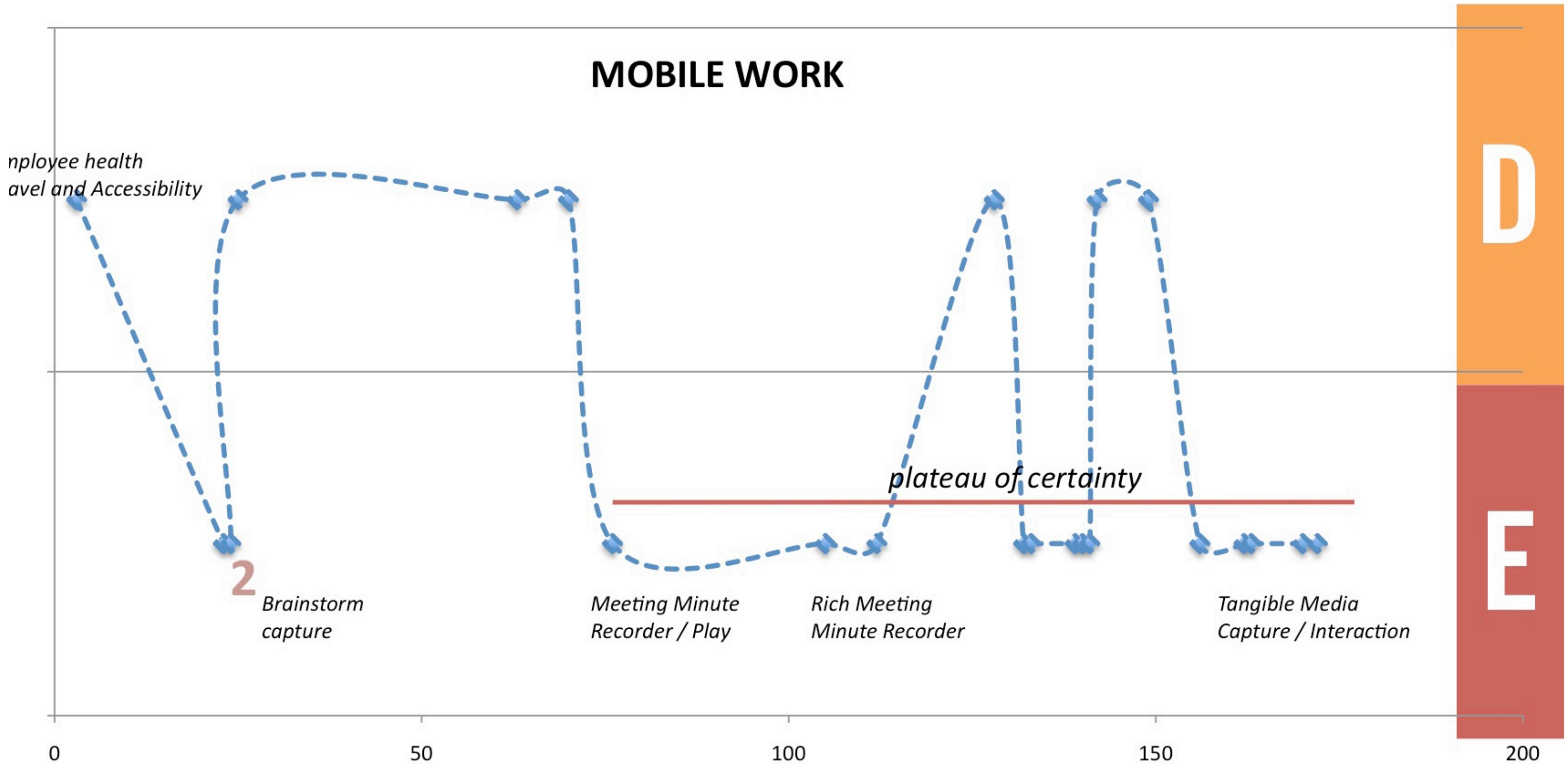

Figure 14. Pivots in project focus are highlighted for one project, time is expressed across the bottom axis

PROJECT MAPS OF PROTOTYPING PATHWAYS

Figure 15, Figure 16 and Figure 17 show the array of prototyping pathways for the nine projects captured in this research. Prototyping activities were plotted over time, with categorizations grouped by conceptual and experiential prototypes and functional part or system prototypes. As with pilot studies described in Chapter 4, the activities of student engineering design projects were distilled to these prototyping pathways visualizations. The prototyping activities were coded along the schema discussed in Chapter 2 and listed again in Chapter 4. Prototyping activities were coded as *designerly* in nature or engineering in nature. The types of prototypes created were plotted on a timeline for team activities.

Prototyping Pathways as Sparklines

These prototyping pathway visualizations are useful as *sparklines* (Tufte 2006). By Tufte's definition, these visualizations are "small, high-resolution graphics embedded in a context of words, numbers, images. Sparklines are data-intense, design-simple, word-sized graphics" (Tufte 2006). A sparkline can be:

> a very simple line chart, typically drawn without axes or coordinates. It presents the general shape of the variation (typically over time) in some measurement, such as temperature or stock marker price, in a simple and highly condensed way. (Wikipedia 2011)

Yasuhara (2011) used sparklines of bar charts to indicate trends of perceived importance of design steps, longitudinally and cross-sectionally (Atman 2010). The visualizations serve to show, at a glance, the activities and practice of the engineering student teams in the course. Relative to each other's progress, and in context to the nature of project briefs, one can see prototyping and project progress.

EVOLVING PROBLEM/SOLUTION SPACE WITH PROTOTYPING

The groups that prototyped more often moved farthest away from their initial concepts. Figure 18 shows the quantity of prototypes created (self-reported) by each team. The range was 14 to 24 over the year. Each prototype served as an opportunity

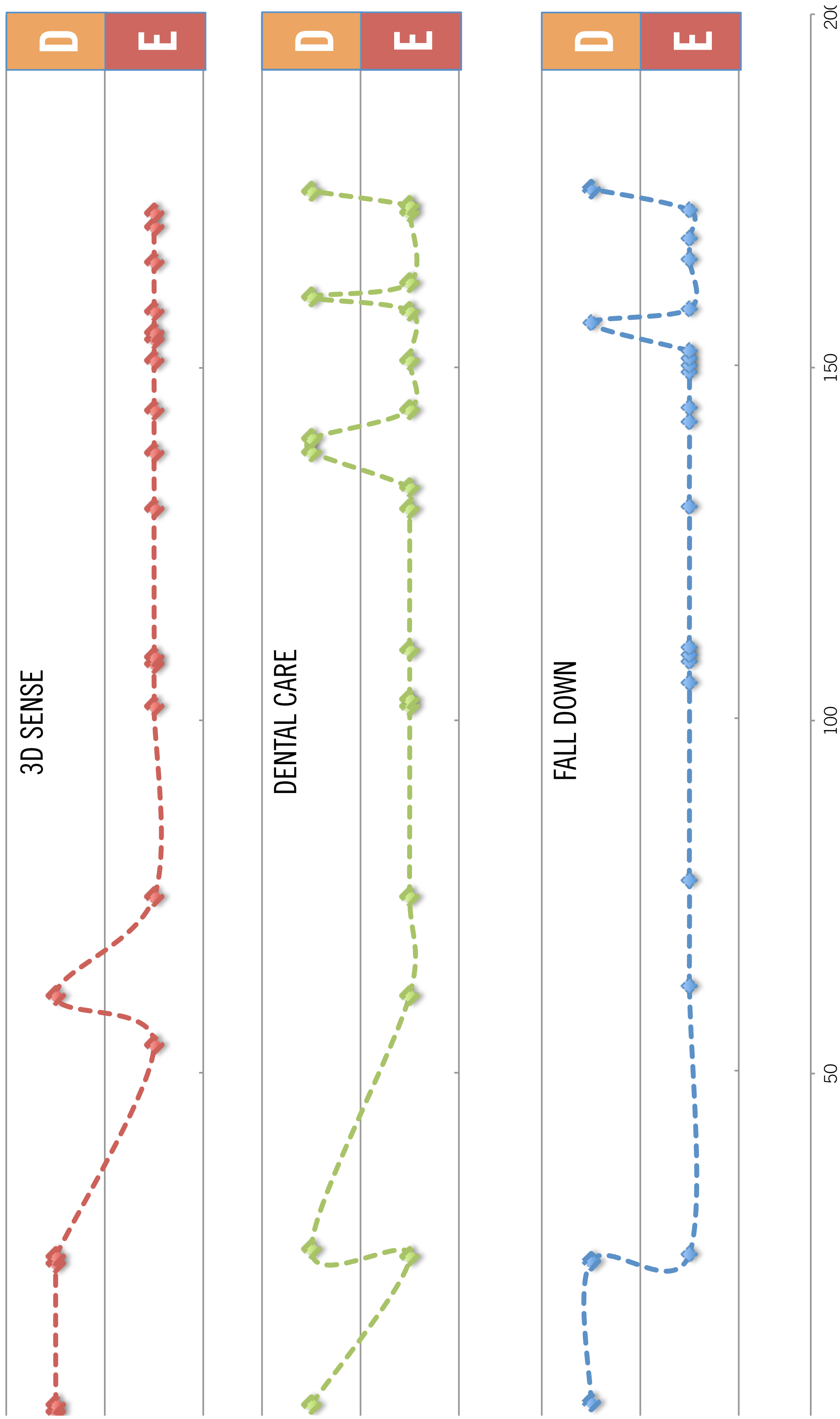

Figure 15. Prototyping pathways

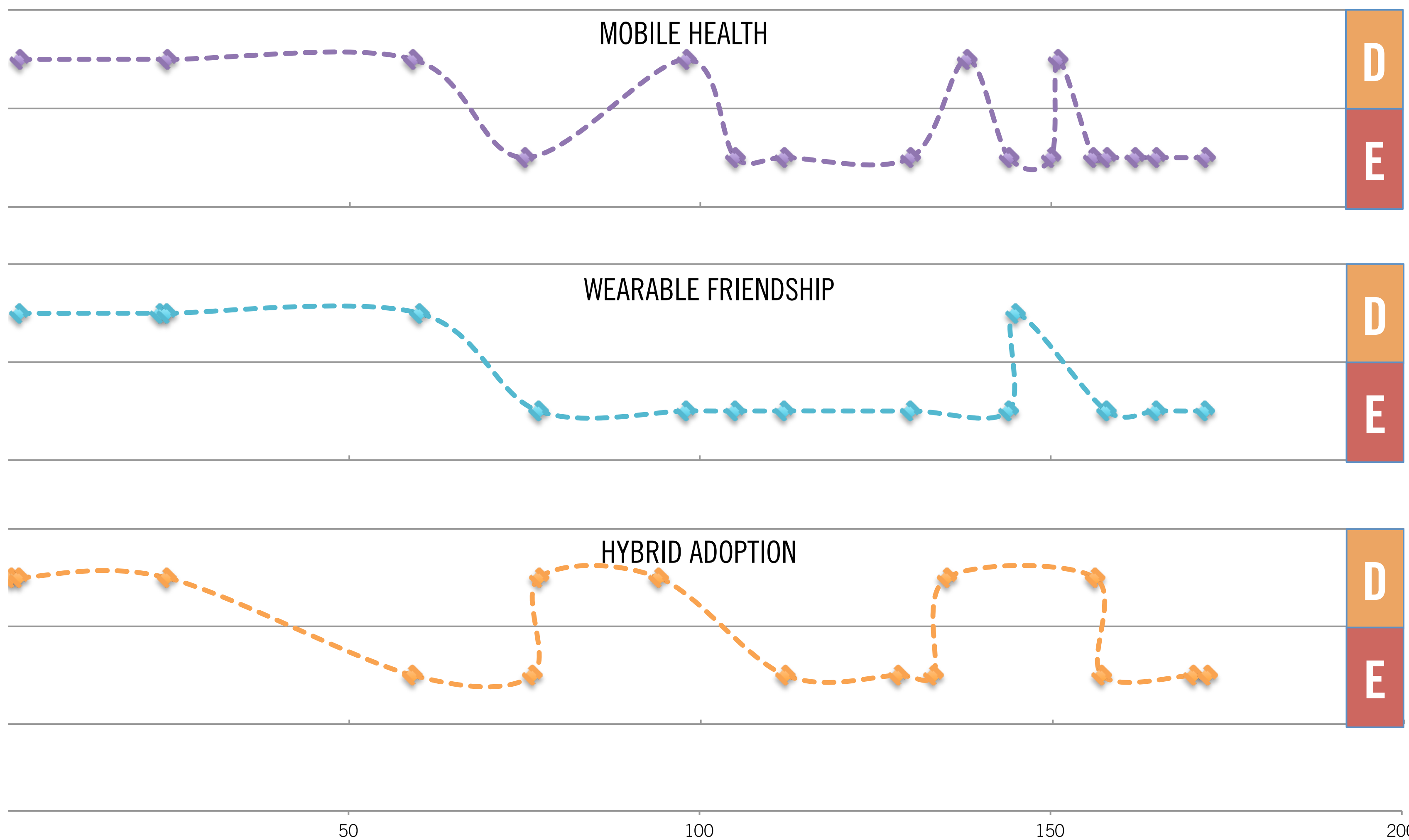

Figure 16. Prototyping pathways

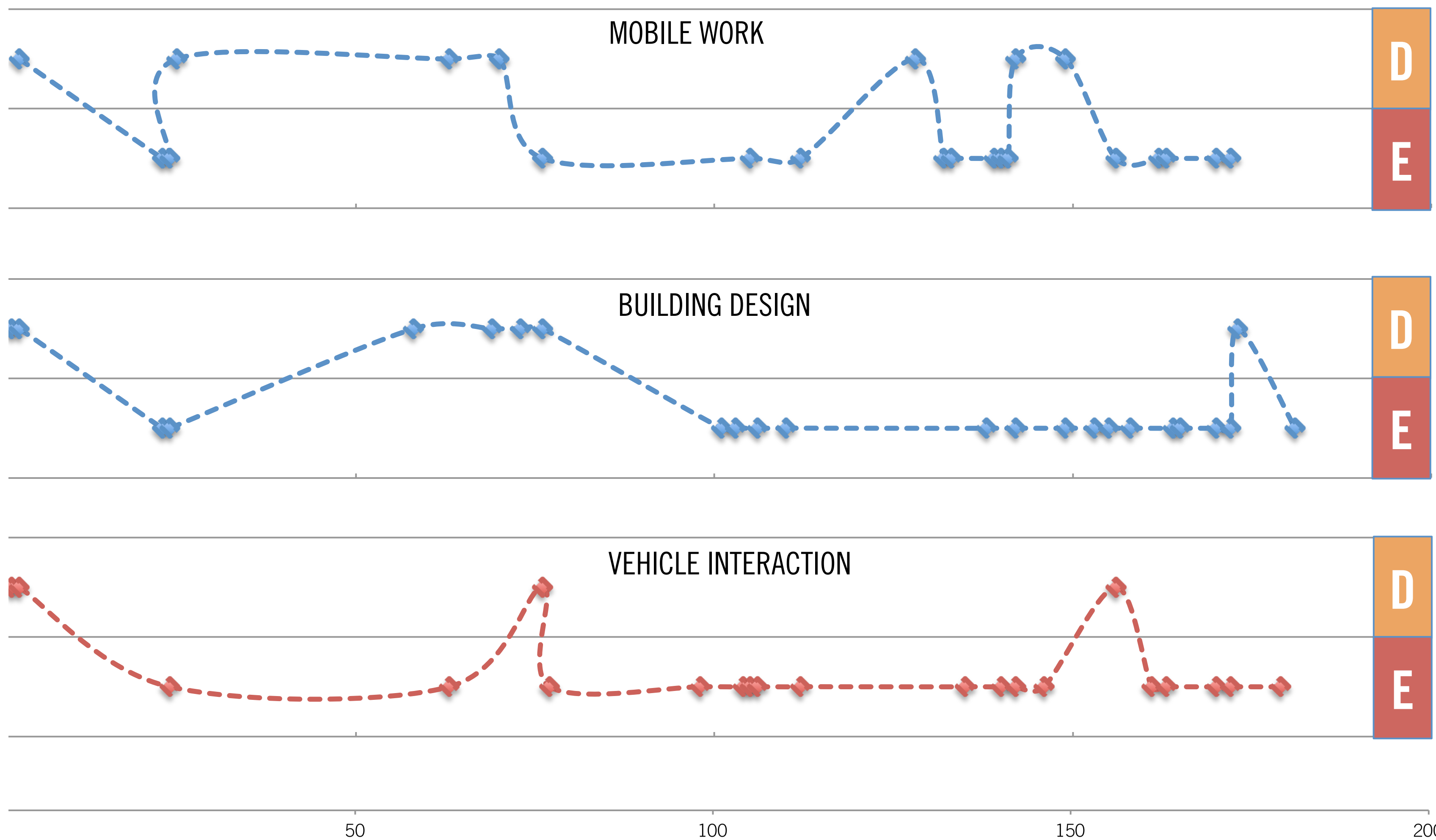

Figure 17. Prototyping pathways

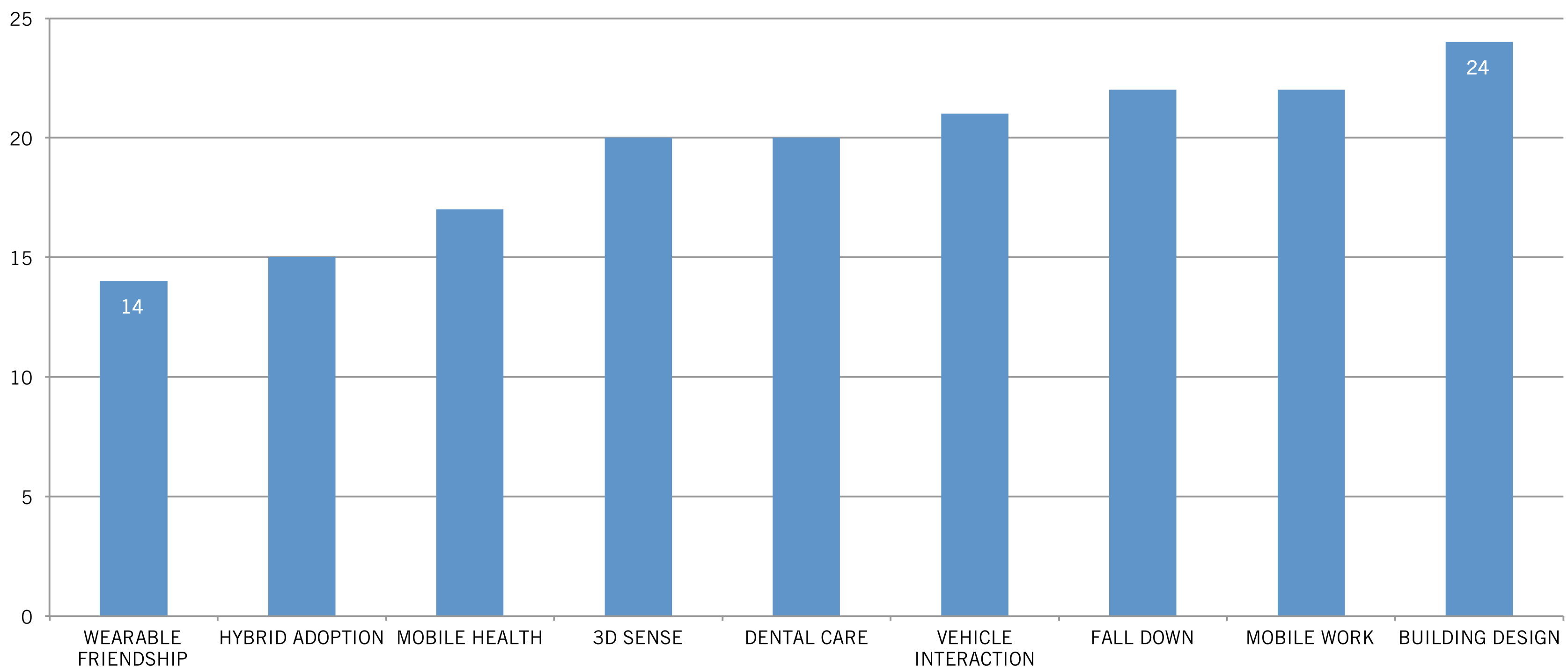

Figure 18. Number of prototypes created by each team.

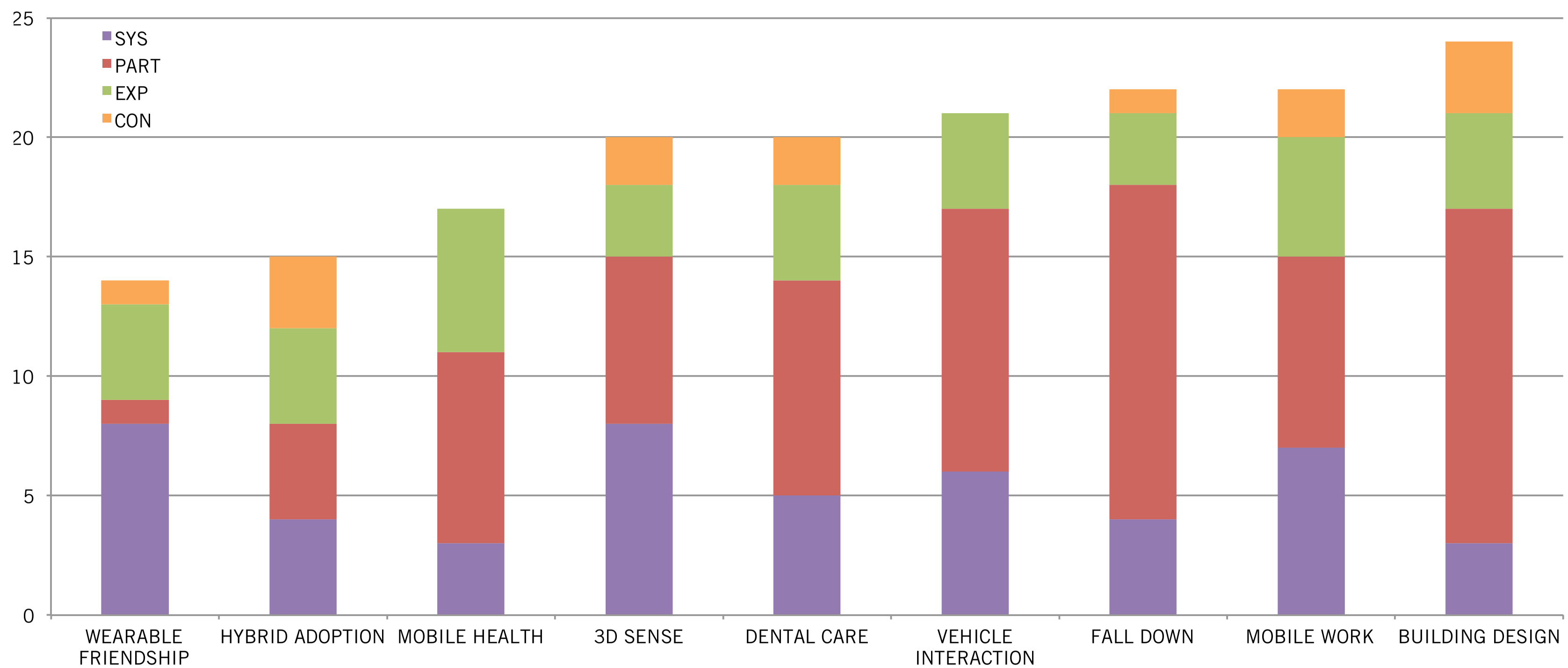

Figure 19. Array of prototypes by classification for each team.

to reexamine and communicate the problem space (Bucciarelli 1996) or to explore the solutions space.

Figure 19 breaks down the array of prototypes by classification for each team. It is interesting to note that the order by total number is commensurate with the amount of functional part prototyping.

An exercise required at the start of the projects was a *2-day design challenge* asking teams of local students and global students (co-located at the very start of their projects) to quickly run through their design processes to deliver a prototype to share and present to their peers in 48 hours. Using this initial exercise as a baseline, both the second prototyping assignment and the deliverables at the end of the year were compared to delineate if teams had ventured far from their starting point or not.

PATTERNS OF PROTOTYPING ACTIVITIES

The less amorphously defined projects arrived at their solution-idea quicker. The point at which the functional idea presented in the final deliverable was settled on by the team was noted (by working backwards from the deliverable). This inflection point is noted in the Figure 20. The inflection point of this idea fixation (Jansson and Smith 1991) and solution focusing (Lloyd and Scott 1994) is noted by a horizontal line notation demarcating at *plateau of certainty*, as shown in Figure 14 as an example with one project, and in detail for each project in Figure 21, Figure 22 and Figure 23. With this example project prototyping pathway map, efforts pivoted from an emphasis on exploring the problem space to refining the potential solution.

Formal Milestones Assignments Versus Informal Prototoyping

Assignments scheduled as course milestones occurred through the year though prescribed assignments were more concentrated in fall quarter. Assignments became less specifically-defined check-ins for winter and spring quarters. Weekly design meetings hosted both formal design review sessions related to these *formal* assignments and additional instances of *informal* prototyping activities.

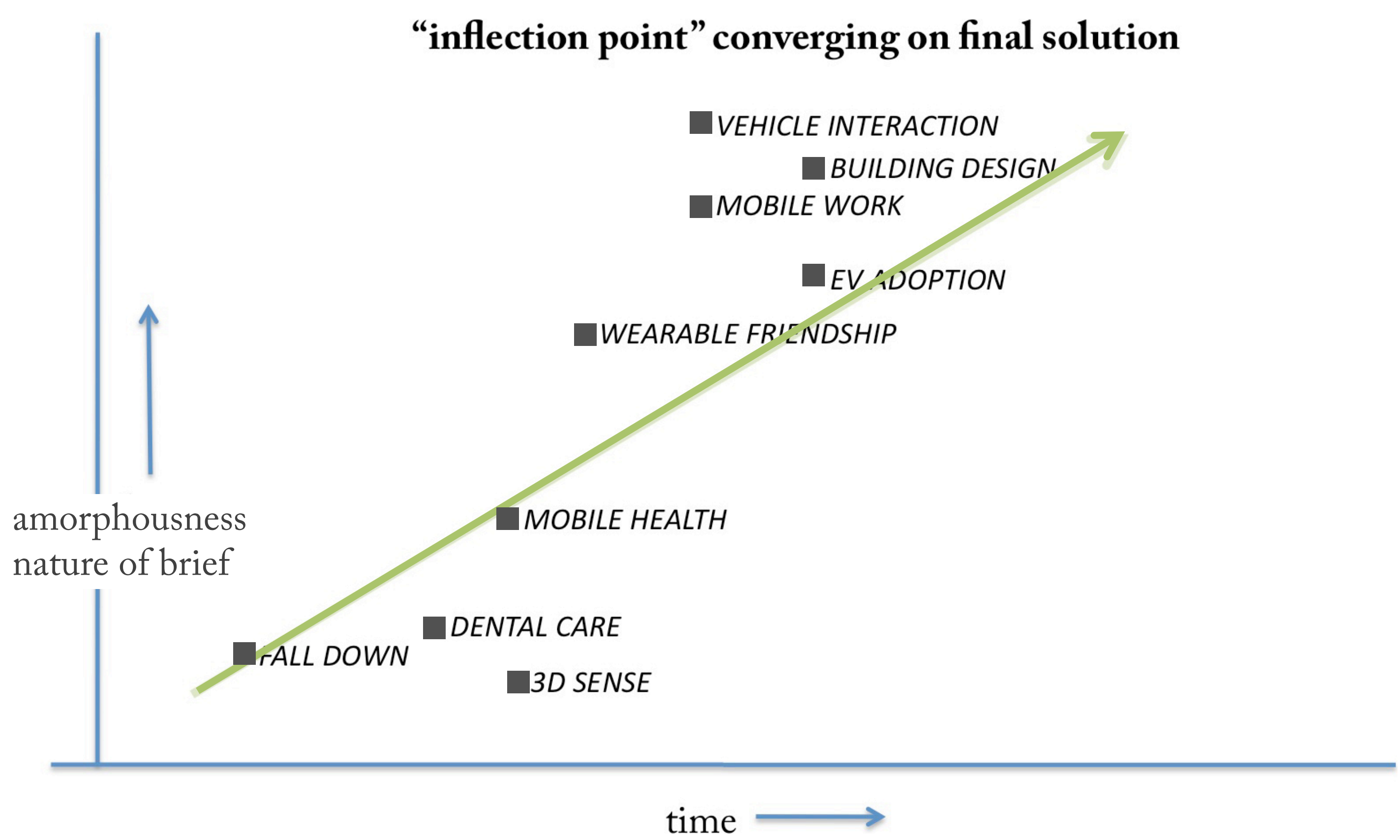

Figure 20. Inflection points of projects with respect to the final deliverable. The inflection point is at the left of each project title.

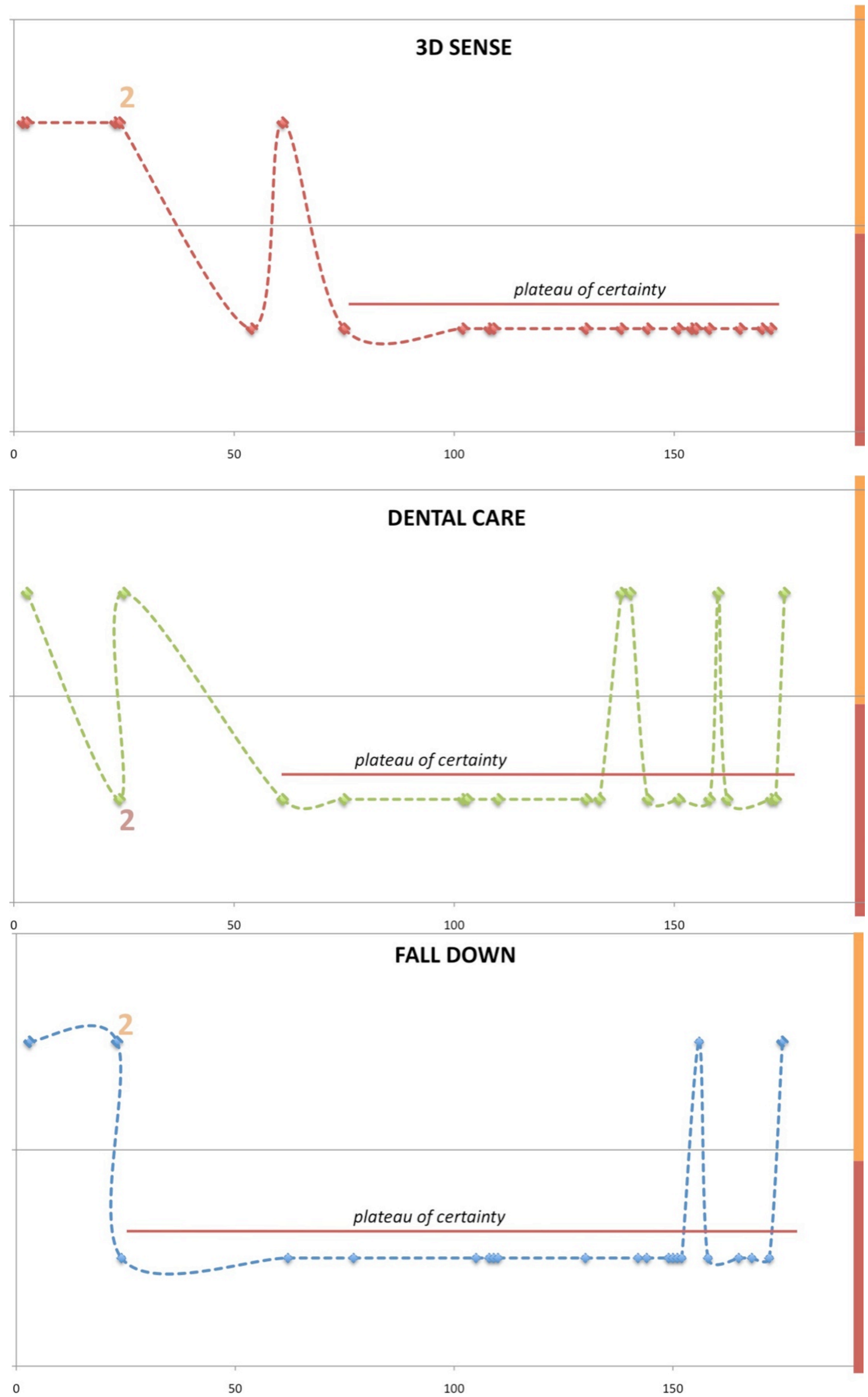

Figure 21. Prototyping pathways with 2nd prototyping move & plateau of certainty

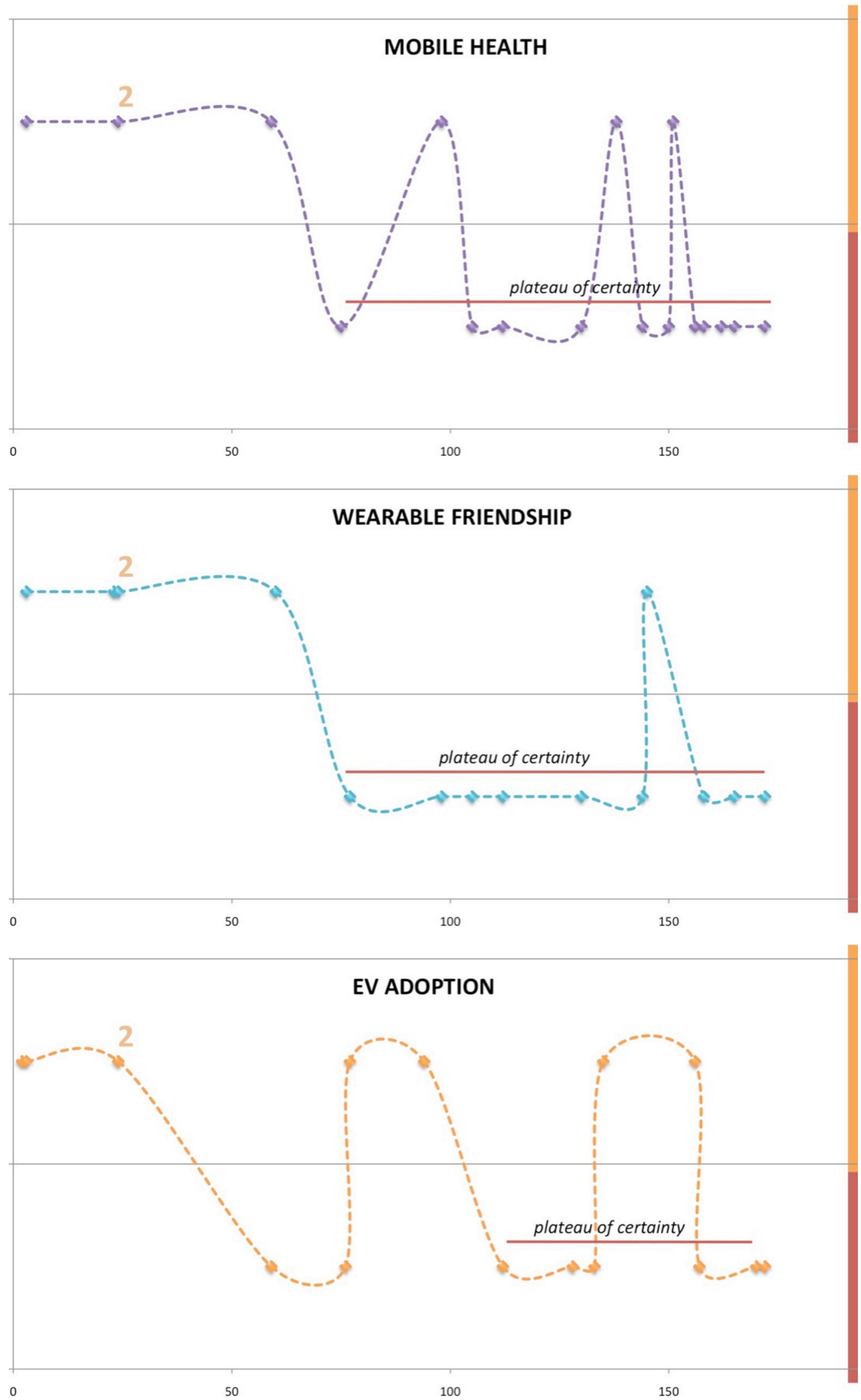

Figure 22. Prototyping pathways with 2nd prototyping move & plateau of certainty

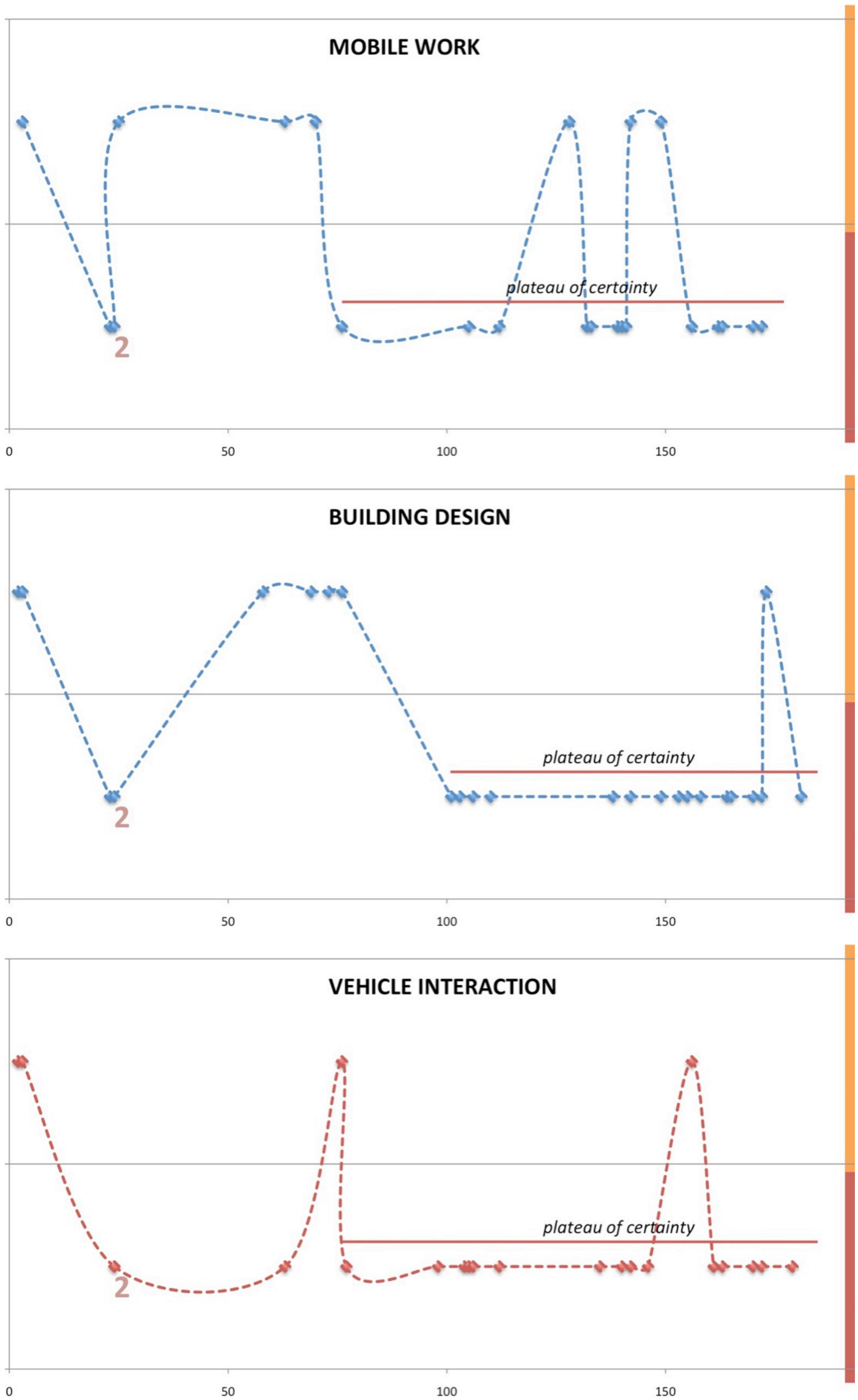

Figure 23. Prototyping pathways with 2nd prototyping move & plateau of certainty

Interestingly, the second assignment – the critical function prototype – and how students teams responded to its request for a *critical component, subsystem or function that makes a difference* (Cutkosky 2009) reflected the type of project classification. This is highlighted in Figure 14 as an example with one project, and in detail for each project in Figure 21, Figure 22 and Figure 23. It is *predictive* of what the students think is the *critical* part of their project. For example, appreciation of what is *critical* allows us to triangulate our analysis. For the less amorphous, projects explored the conceptual or experiential space; for the more amorphous, projects explored the functional part or functional system prototype.

SUMMARY

Capturing prototyping pathways of student engineering design teams was used as a means to explore how engineering students navigate design and engineering activities. The artifacts created were proxies for design steps that can illuminate pathways of prototyping activities, the patterns therein, and an evolving problem and solution space for each of the student engineering design projects.

CHAPTER 7

SYNTHESIS

The first research question of this study is how do engineering students *navigate* among their design and engineering activities? A secondary question is what are the catalysts and barriers to *navigating*? Teams' prototyping pathways were collected and visualized. This was supported by observations of student practice and followed by emergent thematic analysis of data and observations, including student self-reflections. This generated a framework for *Ambidextrous Mindsets for Innovation,*, supported by themes and analytic categories pointing to catalysts and barriers to such actions.

AMBIDEXTROUS MINDSETS FOR INNOVATION

The priorities and guiding principles of design and engineering are distinct, yet complementary. Design thinking is keen on functionality, whereas engineering thinking is high on physicality. Design thinking preserves ambiguity; engineering thinking reduces uncertainty.

Ambidextrous Mindsets for Innovation is a "ways of thinking framework" that facilitates putting design and engineering activities in context in order to make a real impact on learning and life. Previous attempts by the researcher to classify student activities in the Mechanical Engineering 310 course have produced this working framework to model ways of thinking. As illustrated in Figure 24 and Figure 25, it is visually represented as a matrix showing the relative position of Design Thinking, Engineering Thinking, Production Thinking, and Future Thinking.

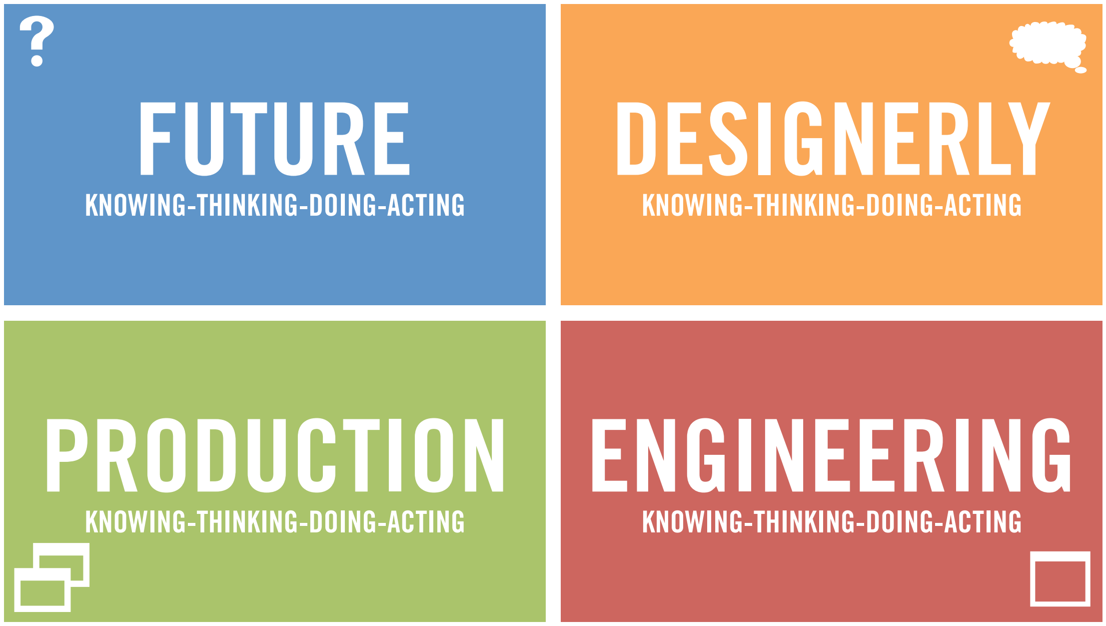

Figure 24. *Ambidextrous Mindsets for Innovation* framework

The activity of Design Thinking is to conceive and *solve a problem* with the end results being an *idea*. For Engineering Thinking *making a solution* results in an *artifact* to embody the solution to a defined problem. Production Thinking allows for the *remaking of a solution* with the results being *facsimiles* or plans by which to make copies. Future Thinking allows one to *reset the problem* with the outcome being a *question*. With Figure 24, the Future Thinking and Design Thinking spaces facilitate breakthrough innovation, primarily due to their emphasis on question-asking. Engineering Thinking and Production Thinking, primarily due to their emphasis on building artifacts, facilitate incremental innovation. Future Thinking versus Production Thinking and Design Thinking versus Engineering Thinking, can also be seen along a timeline from immediate to deferred implementation.

Students are designing the future and designing for the future. Within the *Ambidextrous Mindsets for Innovation* framework, change can be made by:

- Future Thinking: Change the *question*
- Design Thinking: Change the *solution*
- Engineering Thinking: Change the *artifacts*
- Production Thinking: Change the *production process*

The first two are in the functional space – what can be imagined to address the function necessary to solve a problem The last two are in in the physical space – what can be made in service to that functional goal. Existing sustainable design practice and sustainability efforts focus on engineering and production issues. These are defined as incremental innovation. Efforts to reframe and redesign, in contrast, result in a change in paradigm and possibilities.

This research 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.

Distinctions between the Design Thinking and Engineering Thinking mindsets are proposed as catalysts for mechanical engineering students learning design thinking. The implications suggest educational benefits to mechanical engineering students developing judgment through an ambidextrous navigation of Design Thinking and Engineering Thinking activities.

Previous efforts by the researcher to classify student activities has produced this working framework modeling *Ambidextrous Ways of Thinking* (Lande 2009, Lande 2010) as accessed by mechanical engineering design students. As shown in Figure 25, it is visually represented as a matrix showing the relative positions of Design Thinking (Dym, Agogino et al. 2005), Engineering Thinking (Robinson 1998; Cardella 2010), Production Thinking (Beckman and Barry 2007), and Future Thinking (Saffo 2007). Along the vertical axis is a spectrum from incremental innovation to *breakthrough innovation* (Stefik and Stefik 2004). Along the horizontal it is measured in time, from long-term to more immediate, short-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 (hardware or software)*. Production Thinking

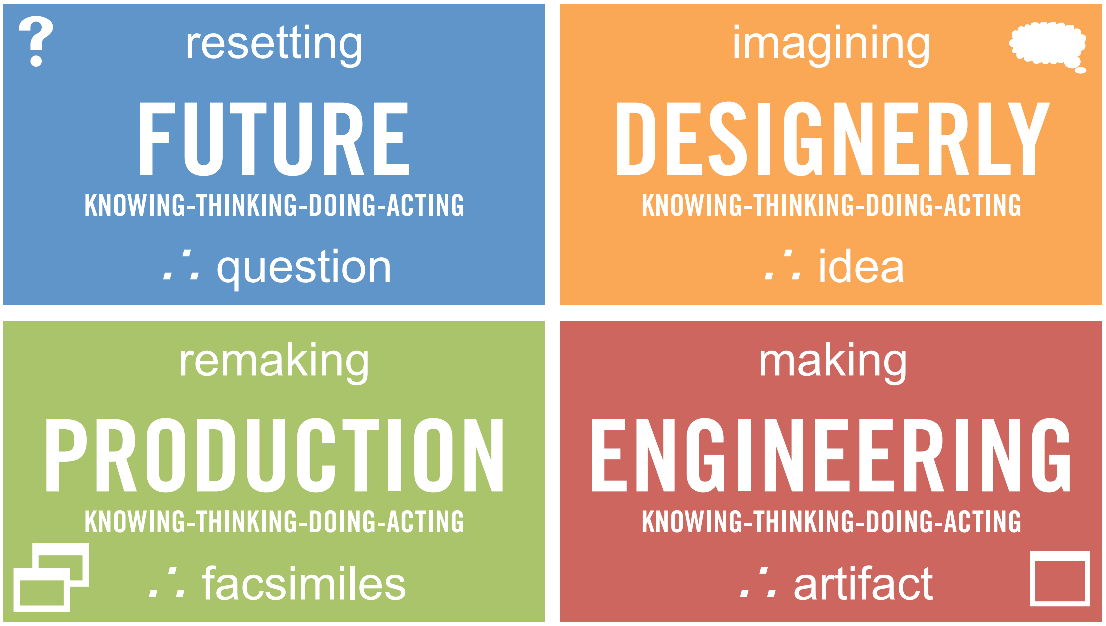

Figure 25. *Ambidextrous Mindsets for Innovation* framework, with definitions

allows for the *remaking of a solution* with the results being *facsimiles* or plans by which to make copies. Future Thinking allows one to *reset the problem* with the outcome being a *question*. The concept of mindsets has been used to differentiate a fixed versus changing outlook on learning and life (Dweck 2007). Dweck has popularized the phrase "mindset" and associated the fixed versus changing orientation. This work and the research presented here is agnostic towards that differentiation. "Mindset" is applied to describe a set of values, priorities and interests, such as a *designerly* or *engineering* way of thinking.

Functionally-Fixated Versus Physically-Fixated

An illustration of a perceived difference between designers and engineers is exhibited in the form of the "how many people does it take to change a light bulb?" joke (Lande and Leifer 2010):

> Q1. How many designers does it take to change a light bulb?
> A1. Does it have to be a light bulb?
>
> Q2. How many engineers does it take to change a light bulb?
> A2. It depends. How high off the ground is it? What is the wattage?

In this pair of parables the designer is focused on the functionality of the light bulb whereas the engineer is focused on the physical aspects of the artifacts. They may have the same intent (to change the light bulb) but view the problem and solution set differently.

Needs Pull Versus Opportunity Push

Balancing an external perceived business opportunity with an explicit or implicit perceived need from a user is also another basis for comparing: whether it is the evidence supported by fiscal possibilities or needs pulled from careful, mindful, and deliberate methods (Faste 1987; Patnaik and Becker 1999; Beckman and Barry 2007; Patnaik and Mortensen 2009).

Ambiguity Versus Certainty

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, students' experiences and graduate careers have been framed in closed-end problem solving. So there is a balancing between preserving ambiguity and eliminating uncertainty (Cardella and Lande 2007), which can be 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 focus on the elimination of uncertainties (Stacey 2003).

Divergent Versus Convergent

The ebb and flow of the engineering design process has been described as a balance of divergent and convergent activities (Eris 2004; Dym, Agogino et al. 2005; Brown 2009). Divergent activities are typically assigned to *designerly* ways of thinking and convergent activities assigned to engineering ways of thinking.

Innovation

In consideration of the very nature of innovation, incremental innovation can be contrasted with breakthrough innovation (Stefik and Stefik 2004; Christensen, Horn et al. 2008; Brown 2009; Martin 2009). What is hoped for, and what is attained, with innovative activities, small steps forward or creative leaps ahead, can also be grounded in the *Ambidextrous Mindsets for Innovation* ways of thinking framework.

SUMMARY

Robinson (1998) has described engineering thinking and rhetoric, elaborating on simple and compound problem solving. In a parallel construction to Cross (1982), we call this an engineering way of knowing, doing and acting.

Since the ME310 design engineering and research test bed is available with engineering students right in the midst of the design process it seems congruent to overlay the traditional design process model on top of the ways of thinking *Ambidextrous Mindsets for Innovation* framework. Much engineering education and design research focuses on what happens in the *designerly* and *engineering* spaces and it aligns with steps in an engineering design process, with contrasting values, priorities and motivations within each.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Designerly ways of knowing and *engineering ways of knowing* are characterized in mechanical engineering design practice as *Ambidextrous Mindsets for Innovation*. *Designerly* and *engineering* approaches are complementary yet distinct by areas of concern (*ambiguity* vs. *uncertainty*), fixation (*functional* vs. *physical*), innovation style (*disruptive* vs. *incremental*) and priority (*framing* vs. *implementation*). Habits of mind contribute as catalysts or barriers to such innovation.

Iterations of prototypes made in creating a physical or tangible artifact are evidence for design learning. Prototypes serve as tools for communication and exploration as well as means to answer questions internal and external to a team. Categorizing prototypes as *designerly* (conceptual and experience prototyping) or *engineering* (part and system prototyping) can map and document engineering design activity. The prototyping stream develops team collaboration towards innovative outcomes and individual positive epistemic identities on designing and engineering practice. Different sorts of projects (ambiguous/specific future-design-engineering-manufacturing areas of emphasis) follow different patterns of prototyping and practice. Being aware of the possible prototyping pathways can have a very real impact on planning for future resources.

CONTRIBUTIONS

The results of this research can have direct impact on design teaching pedagogy. They also give industry new methodology for managing disciplinary collaborations. By delineating a distinction between *designerly* and *engineering* ways of knowing, more mindful interventions are available. Better informed coaching interventions are possible by taking into account differing Prototyping Pathways for different types of projects. Teams and individuals are encouraged to iterate among these *Ambidextrous Mindsets for Innovation*, resulting in better learning outcomes and better design outcomes. The engineering design teams that take more jumps across their design and engineering activities (over iterative loops within) both achieve a higher level of novelty and innovation in deliverables and have better learning experiences by co-evolving the problem and solution. The *Ambidextrous Mindsets for Innovation* framework has been adapted to redesign the curriculum for the ME310 mechanical engineering design and innovation course at Stanford.

IMPLICATIONS FOR COURSE CONTENT

The core programs and courses of mechanical engineering design experienced by design and engineering students at Stanford University can be overlaid onto the ways of thinking framework, shown in Figure 26.

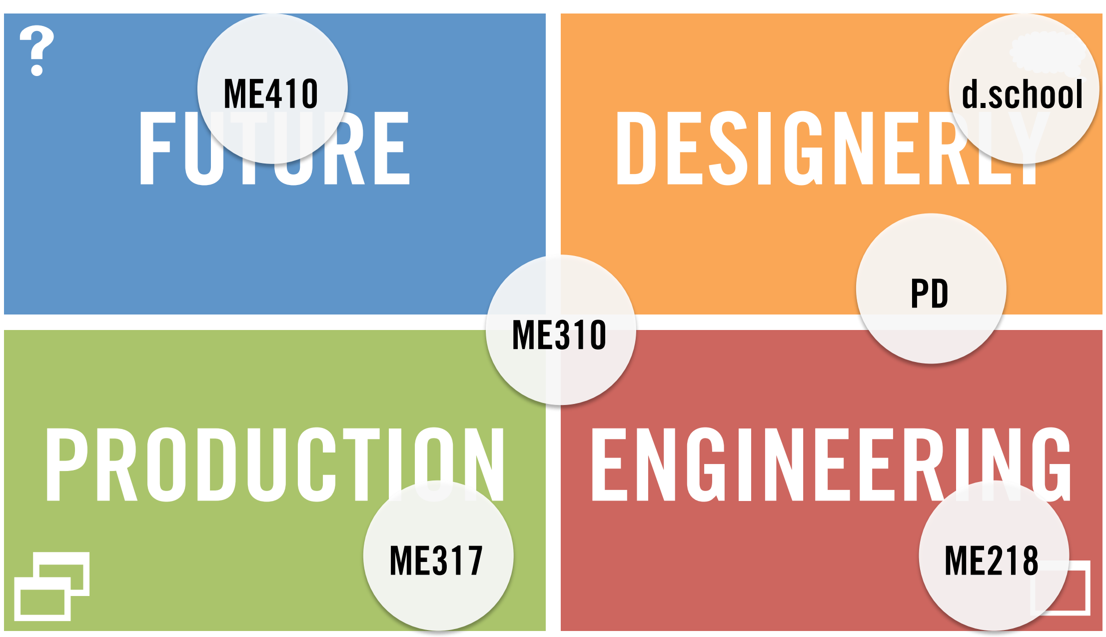

Figure 26. Framework applied to selected mechanical engineering design courses

Courses in designing the future and foresight methodology such as ME410 Foresight and Innovation serve to cover the Future Thinking space. The Joint Program in Design and Product Design programs as well as classes under the auspices of the Hasso Plattner Institute of Design (d.school) include projects and classes that focus on the functionality of the design or artifacts. Of note, Future Thinking and Design Thinking spaces tend to focus on functional aspects over physical aspects. There exist courses that do emphasize the physical aspects of design and engineering. In the engineering space ME218 Smart Product Design is a skills-based electro-mechanical core course. In the Production Thinking space, ME317 Design for Manufacturability exists as an historic outgrowth of ME310 that deals with issues of manufacturing and production. Interestingly enough ME310 lives in the middle of the array, covering aspects of Design Thinking and Engineering Thinking but also touching on Future Thinking and Production Thinking.

The complementary nature of *designerly* and *engineering* course content can be made explicit. Students and faculty alike can more mindfully chart (or help chart) a learning career balancing technical material. Such a mapping will help guide students and help faculty differentiate, highlight and synchronize their offerings. This supports students becoming innovators themselves.

RECOMMENDATIONS FOR DESIGN LEARNING

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. Designing often requires a new approach to problem solving and, as such, the ordering of project objectives is 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 toil on close-ended problems in the form of problem sets. Upper-level classes focus, in contrast, on open-ended problems and collaborating in groups, approximating practice one might find in industry. For some students, the switch is harsh, or at least, seemingly arbitrary. For others, the change is welcome. Doing problems individually differs greatly from collaborating in a team to solve some open-ended, authentic situation. Engineering education is moving towards the development of engineers who can both ask better questions and answer them more creatively. Incorporating design thinking, prototyping skills are a key element in the new paradigm. Observing student engineers learning a design process in the safe environs of a Master's level course allows easier observation and analysis of their design activities than is possible in professional industry setting.

For mechanical engineering students, especially the cohort of Master's students observed in this study, their prior exposure to Design Thinking was, for the most part, very limited. At most, they might have been exposed to Design Thinking and design activity through a single capstone mechanical engineering course or had summer internship experiences in industry. Projects are typically focused on mechanical engineering machine optimization and redesign tasks. It is rare that people are included within the system definition. In contrast, students have more exposure to and experience with Engineering Thinking activities, focused on the implementation aspect of the design process This focus echoes the engineering fundamentals that are an overwhelming factor in most undergraduate curricula.

The design process model overlaying this framework is another area that could benefit from further investigation. It is the author's intention that this model of the design process in undergraduate and graduate education scaffolds the mental models and could support a transition from a simple novice model, to a more intermediate, and finally to an expert model. Hopefully, the students' representation of the design process either reported individually, or in their design documentation as a team, could be one means to assess student learning in engineering design courses. It can be imagined that individuals' models of the design process fall along a spectrum. Considering individuals' process models would be another factor of diversity to consider in team formation in engineering design.

RECOMMENDATIONS FOR FURTHER RESEARCH

The research to date has focused on steps mechanical engineering design students take in their design processes. Further investigation will add to this research direction by focusing on the following topics:

Future + Designing & Engineering + Production

Extending the Ambidextrous Mindsets for Innovation framework to both additional sphere of concern in Future and Production/Manufacturing Ways of Knowing as well as applying this approach to additional domains is of immediate interest.

Imagining and Making

Engineering and design are professional activities. This research plan asks 'How do these practices translate to a K-12 setting and how can imagining and making skills be taught to a younger population?'

Breakthrough and Incremental Innovation

In mature and new fields alike, creativity and innovation are often claimed as factors for success. This research plan explores how established and start-up companies, entrepreneurs and venture capitalists, innovate and the strategies and methodologies they employ in their design process. Particular interest is in capturing and describing instances of breakthrough and incremental innovation.

Design Thinking to Engineering Doing

By observing mechanical engineering design students and practitioners *in situ*, early conceptual design phase and engineering implementation activities will be further characterized. In addition, the transition from novice to expert will be explored.

Design for Future-Oriented Visions

More and more, mechanical engineers are being asked to tackle ill-defined, wicked real-world problems that exceed the bounds of traditional mechanical engineering.

This research plan proposes exploring how engineers approach amorphous design prompts and calls for designing out 5+ years into the future.

Popular Conceptions of Design and Engineering

This research plan investigates how Engineering is represented as a professional endeavor in popular media and how K-12 students and parents conceive of and understand Design and Engineering roles and activities.

Figure 27. Products as illustrative examples of Design & Engineering Thinking, Apple iPhone (left) and RIM Blackberry (right)

Company Innovation Mandates

An attempt has been made to identify, define and distinguish Design Thinking activities from Engineering Thinking activities. An illustrative example (Figure 27) compares the features and users descriptions of the Apple iPhone compared to the RIM Blackberry phones and experiences. For the iPhone, it is often said that it is an elegant aesthetic design, the user interface is lauded and its role as part of a larger product family ecosystem is mentioned. For the Blackberry (now fast becoming dated technology), it is the physical keyboard and a feature set that pushes e-mail to the device that is most often highlighted. There is a tension between the functionality (iPhone) and physicality (Blackberry). The distinction exemplifies a distinction between Design Thinking versus Engineering Thinking. What does this look like in a company setting?

Engineering Student Design Learning: Longitudinally & Cross-sectionally

Most students have been exposed to some design or design methodology. Their experience, though, is limited to learning what some of the design steps may be, and practicing them to synthesize their capstone engineering undergraduate project experience. For these students, their conceptual understanding of the design process is a very simplified, linear one. As hands-on prototyping activities occur and students step through the design steps in any mechanical engineering course what becomes of interest is how their design process representations becomes more nuanced, showing evidence of iteration and flexibility, and design learning.

Students' concepts of the design process develop from a novice, linear design process at the start of the course to something that is more iterative at the end of the course. (Student concept maps were collected at the start of the course and subsequently at the end of fall, winter and spring quarters.) Often, the students know their engineering content knowledge, but what is added is the concept of needfinding and observation in the fuzzy front end of the design process. Student concept maps of their typical design process change from first to second quarter to show inclusion of a person or user as part of the envisioned system. As students step through and experience, their project activities, their concept maps of the design process in mid-course as well as at the end of the course are, understandably, more developed. Student concept maps begin to show iteration and connection of design steps in a loop or continuing manner (Adams 2001). Some concept maps at the end of the course show a change from a routine step through the design process to something that is more adaptive (Lande and Leifer 2009).

Further exploration of the epistemic identity of design learners via a Design Learning Trajectory (Figure 28) from routine design practice to adaptive design expertise is suggested. By capturing concept maps that reflect their mental models of the design process, students can be placed along a novice to expert design continuum

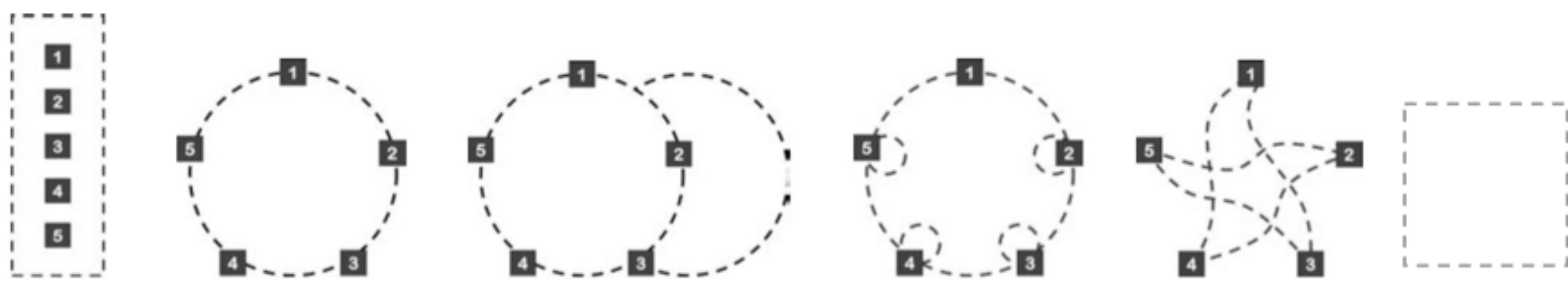

Figure 28. A proposed design learning trajectory.
Student concept maps of their design process grow from simple, linear representations to more involved circular and iterative models, to more ad-hoc representations of adaptive paths of experience.

using an assessment tool based on their understanding rather then on their output. This can be useful as both a formative and summative evaluation tool.

It is anticipated that this research will contribute to a means for assessing student learning in design courses. Additionally, this line of research can be extended to examine how students and industry professionals learn and practice design. What and how students learn in the classroom and how that relates to what they face in their professional life is also of great interest.

RESEARCH REFLECTIONS

The researcher's field is mechanical engineering design. In a very real way, it is about addressing and solving real, ill-defined problems. There is excitement in helping students judge the best problem to solve and thinking critically and creatively, abstractly and concretely, to address it. This is what design is for me – using the most *appropriate* method to discover the *best* question.

From my point of view, the variety of hands-on, project-based-learning design courses' authentic and adaptive experiences enable students to achieve both task and learning results. My experience is that students are well served in these types of courses. Teaching mechanical engineering through a project-based-learning approach and introducing a design thinking process to engineers, is an increasingly popular and, for me, an exciting way to aid students' learning.

I enjoy seeing students as learners and witnessing how their problem solving skills mature. The students develop judgment in parallel to skill building. And I like to teach students at transitory stages in their intellectual careers: (1) moving from the certainty of math and science in K-12 to self-directed learning expected in university; (2) stepping from the closed-ended problems of early mechanical engineering education to the ambiguity of open-ended problems in team and project activities; and (3) transferring theories of engineering systems to applications in capstone.

I have seen hands-on tasks and I have experienced active learning as inspirationally invigorating and mutually rewarding for students and teachers alike. If we are to prepare students for future careers in industry, then it is best to equip students to know how to frame problems, where to search for help and how to engage others, in addition to their fundamental engineering content knowledge. Having students continually reflect on their practice and process along the way, through design notebooks, learning portfolios and classroom exercises, makes for a genuine, enduring learning career. By following up with students' prototyping activities with questions of *what did you learn from this?* and *what questions were you answering?* I have found students eager to be reflective about their practice.

I find that asking students to consider solution spaces beyond just technology implementations, to considering user and social implications, to be highly instructive. For mechanical engineering students, pushing their design of systems to include human concerns serves to increase their capabilities. Within the relatively risk-free environs of the classroom, failure is a learning tool; students should feel free to experiment and push out the boundaries of their knowledge and comfort. Engineering design courses that I have taught all had themes that went past traditional mechanical engineering systems. With a user-centered design approach, students can be asked to extend their design processes to solve any problem and develop self-efficacy to get things done.

Design is among the disciplines that can significantly impact the world around us. The acts of observing, conceiving, and implementing make design and engineering design important activities for those concerned about the world we live in. An approach, geared towards *sustained* real impact (Lande, Adams et al. 2007; Lande and Leifer 2010) and *sustained* breakthrough innovation (Stefik and Stefik 2004), is to shift the frame of these growing issues in a different way. We require design thinking education practice that seeks to change the context dramatically and break the mold of current means of thinking. It must be more than plainly engineering better solutions and to implement better technology. Engineering students should be asked with each problem faced not just to re-engineer and re-manufacture but to re-visit the problem space and re-define the questions asked in the first place. This makes design and design thinking (Dym, Agogino et al. 2005) especially relevant for the ill-defined, wicked problems (Buchanan 1992) of today. This is designing for the future, for tomorrow – to have beneficial impact on our world for generations to come.

It then surprises me to find excitement in industry and academia around design, engineering and innovation. And it frustrates me to see timid incremental change in adoption of a *designerly* approaches. The *Ambidextrous Mindsets for Innovation* framework gives a constructive basis to imagine and make the future of innovation and future of engineering design education.

APPENDIX

HUMAN SUBJECTS PROTOCOL

Designer Behavior Study

Stanford University Human Subjects in Non-Medical Research Protocol ID: 10646
Protocol Director: Larry Leifer

Qualified staff The study will be set up and conducted by Malte Jung, Jonathan Edelman, Micah Lande and Neeraj Sonalkar. The same persons will also conduct the data collection and analysis. Each member of the staff will focus on a different aspect of the study. The entire team is necessary to cover the different aspects of the data collection and analysis process. The analysis of the audiovisual data requires additional students to code the data who are blind to the hypotheses of this study. All other students will have complete IRB training before having any access to the data.

Training All researchers have been involved in the conceptual development of this study. The research team will inform everyone in person and with a written protocol about the details of the study. A checklist will ensure that all researchers (and specifically additional students who analyze the data) are informed about the protocol and their duties during the study and during data analysis. Every researcher and coder will receive specific training to ensure that the privacy of the subjects will be maintained at all times.

Facilities Facilities to record video and audio data will be required for certain portions of this study. The study requires that there are up to 4 video streams and 1 audio stream recorded simultaneously. The multiple video streams are necessary to allow that a separate video stream can be used to capture the activity of each individual participant. Individual streams are necessary as the analysis procedure requires a good reading of the subjects to allow the analysis of their behavior. One audio stream is necessary as the analysis needs information from the spoken dialogue of the subjects as well. The study has to be partially conducted in a separate room. This is necessary to ensure that no distraction occurs throughout the time of the study. The other part of the study will involve observations in the ME310 classroom space. The required facilities are readily available in the Design Observatory at the Center for Design Research. This equipment is ready and doesn't require additional modifications in order to be used for this study.

Time The research team will have sufficient time to conduct and complete the research. The data collection will occur at several points during the Fall, Winter and Spring Quarter of the 2008-2009 academic year. The time frame spans the duration of the ME310 class. Observations and analysis of data will be recorded videos and surveys can be continued into the following year if necessary, since the data will be preserved and accessible to the researchers beyond the current academic year.

Access to target population The main participants will be design teams from the ME310 class. Personnel are all graduates of the ME310 class and have stayed in touch with the ME310 community since taking the class. The research team will have access to the entire ME310 class, a Master's level engineering design course at Stanford University in which close to 40 Stanford students participate in up to 11 collaborative team projects sponsored by industry affiliates The class is tightly integrated with the research conducted at the Center for Design Research and students are aware of the benefits. The guiding questions for this study are: what do designers do when they do design? and what can we do to increase their performance?

Access to resources if needed as a consequence of the research The research team doesn't anticipate any medical or psychological resource needs arising as a result of the research. As all students are required to have health insurance, should they need any of these resources for any reason during the course of this study, they are available through the campus health center and participants' health insurance.

Purpose In this study we want to observe student design teams at work. From these observations and our collected data we want to derive recommendations to improve design team performance. Our research focuses on aspects of team dynamics, work habits, prototyping and the evolution of the design problem. We want to utilize a multi-method data collection approach consisting of ethnographic observations, surveys, interviews, logging of electronic design activity and audio-visual recordings.

Goals We hope to understand the effect of team dynamics, work habits, and information sharing on performance of design teams. The new knowledge generated will hopefully help to improve the performance of design teams. Every academic year in the ME310 class there is a wide spread in team performance. Given that all teams have access to similar design resources and work under similar conditions, we expect that other factors like team dynamics, work habits, etc., might cause the difference in performance. Hence, it is important to understand the factors that cause these differences in performances. This is often reflected in a weak performance leading to a non-optimal grade or even results in team members leaving the course. Knowledge about these internal processes that lead to these undesired outcomes will allow instructors to support a design team in a way that will improve its performance and lead to a more positive experience for the students involved.

Study Procedures We will use the following standard research procedures: (1) Ethnographic observations of design teams at work and during interaction with instructors and coaches. (2) Audio-visually recorded semi-structured interviews with students, instructors, industry liaisons and coaches. (3) Surveys created based on ethnographic observations and student comments during interviews. These surveys will consist of questions regarding their design experiences, results and work habits.

(4) Logging of design activity events by capturing internet-enabled information exchange directly related to the project. (5) Video-taped student teams during a lab exercise. Each lab will not exceed two hours. During the laboratory exercises the students will be asked to work on a short design task and discuss topics regarding their design project. (6) Audio-visual recording of team design meetings that are a part of the normal class activity. These are the least risky procedures that can be performed consistent with sound research design.

<u>Risk</u> To our knowledge, these are the least intrusive and least risky methods of capturing relevant research data about team dynamics, work habits, prototyping and the evolution of the design problem and of ascertaining to what extent these factors affect design team performance and the overall design activities they engage in. Deception will not be used.

<u>Background</u> All members of the research team have participated in ME310 and other design courses as students and/or instructors and found the variability of the design performance between teams to be due to differences in team dynamics and work habits rather than technical issues since all teams operated under almost identical conditions form a technical view point. The research of our team builds on a long tradition of design researchers at the Center for Design Research who have been studying designers with the ME310 class. This study will extend the previous knowledge in order to integrate some of the earlier findings.

<u>Participant Population</u> We expect between 40 and 50 students from the ME310 course to enroll at Stanford. In addition, we expect participation from 10 to 15 persons from the teaching staff of ME310. Additional 50 to 60 visiting students who are collaborating with the ME310 teams will participate for limited duration. The total number of participants at all sites (including Stanford) will be expected to be between 60 and 100. Participants will be students, instructors, industry liaisons and coaches. Student teams will be used because within the framework of a design class they are all working on comparable tasks. Further the performance assessment is already being done by the teaching team. In addition the teams will benefit directly from the

feedback that is provided as a result of this study. The study will involve industry liaisons and coaches in order to get an independent view of the design activity.

Demographics The population will be male and female with diverse racial and ethnic backgrounds, and mostly between the ages of 21 and 30. A few participants will be up to 70 years of age. No participants will be under 18. Approximately 100 to 120 participants will be subjects in this study. Students were chosen because they work in small teams on design projects and because this research is aimed at improving the performance of teams in academic design projects. In order to minimize risks and chance of harm to the participants, data obtained through video-recordings, surveys or interviews will be stored securely and will not be accessible to others, including their professors and classmates. Minors are not included because the population being studied are graduate students, instructors, industry liaisons and coaches in the ME310 engineering design course who are all over the age of 19. Between 60 and 100 subjects are expected to participate in the study. All participants will render the same written informed consent. No means of payment are available. All participation will be entirely voluntary and participation in the study will not in any way affect grades or employment compensation.

Recruitment Participants will be identified for recruitment through classroom recruitment. Recruitment will take place by announcement made in class and through email to the list of students in the ME310 course. Our recruitment procedure is to inform all participants involved in ME310 of the study during a class lecture. Everyone will be fully informed about the procedures and benefits of participating in the study and that the fact that participation in voluntary. After this session, we will hand out consent forms and ask for voluntary return to the researchers.

Payment No payment will be made for participation in the study. Students will not be asked to perform any additional work in the course. The only additional contributions that well be expected are involvement interviews, questionnaires and laboratory tasks over the Winter and Spring quarters of the 2008-2009 academic year. No funds are available for payment. No costs will be charged to any of the participants.

Duration The study is expected to last 1 year. Screening of participants should take less than 5 minutes. Active participation will last through the end of the Spring quarter of the 2008-2009 academic year. Active participation should involve between 3 and 3.6 hours time commitment outside of normal class activities per quarter for each participant. Analysis of participant data is expected to last no longer than one year following the study.

Risks (Physical well-being) No potential risks are expected to physical well-being of participants. (Psychological well-being) The only potential risk is the inadvertent release of a participant's name to people outside this study and the impact this might have on the psychological well-being of the participant. The psychological impact of this student does not exceed what can be expected from regular teamwork and group discussion. (Political) No potential risks are expected to political well-being of participants. (Economic) No potential risks are expected to economic well-being of participants. (Social well-being) No potential risks are expected to social well-being of participants. No research will be conducted overseas. (Minimizing risk) The potential risks lie in the exposure of subjects' identities and in the inappropriate use of the information that is collected. The risks of these are very low. To guard against these, all research personnel will be duly instructed about the conditions limiting the use of the data. Data will be stored securely and will be accessible only by research staff of this study. (Intervention) This study will not entail any medical or psychological experiments. Psychological stress does not exceed what can be expected from normal team discussions outside this study. However if any exceptional situations occur, the study will be interrupted immediately.

Benefits Participants will benefit directly because some of the study procedures will directly contribute to the progress of the classwork. In addition they will benefit directly from the team discussion tasks given during the laboratory exercises as they get the opportunity to reflect about their own process. Future participants will benefit from the findings of the study that can be used to give helpful feedback to these teams.

Confidentiality (Procedures) Confidentiality will be maintained by storing the data securely. Only the research staff will have access to any personally identifiable information attached to the data during the course of the study (Maintaining confidentiality) The audiovisual data gained through surveys and interviews will be stored on an external hard drive and kept accessible only to the researchers. All physical records such as sketches made by participants and survey data will be kept accessible only to the researchers in locked cabinets at the Center for Design Research. Samples and records will be labeled with the team names and dates. Only the researchers will have access to sensitive information. All information collected will only be accessible by the researchers. Hard drives with audiovisual records will be kept in a locked file cabinet. Physical records such as surveys and sketches will be kept by the in the laboratory which is secured through a code lock. The code is changed in regular intervals. (Educate research staff) We will require IRB training of all staff members before giving them access to the data. We will also talk with them face to face about the importance of confidentiality and any precautions that they should take to maintain confidentiality. We will provide a checklist to ensure that the data is securely stored after it has been accessed. (Protected health information) It is feasible to not collect and record protected health information. We will not collect and record PHI. It isn't feasible to not collect and record individual identifiable information as part of the analysis method requires audiovisual data of the participants. (Identify) We are not using de-identified data or specimens. The data will not be coded. We will collect and record individually identifiable information both at screening and recruitment, before obtaining informed consent, and throughout the course of the study. We will need to collect the names of participants, the teams to which they belong, and the projects which they are working on. We do not intend to code or destroy the individually identifiable information. We may need to disclose individually identifiable information (audiovisual data and transcripts from the audiovisual data) to other researchers involved with this study.

Consent The researchers themselves will be obtaining content. Consent will be obtained during class time in the classroom of the ME310 class. 10 to 15 minutes are devoted for consent discussion after the study has been introduced. There will be sufficient time and opportunity to consider whether to participate or not. In addition the participants have the opportunity to withdraw their consent at any time of the course. The purely voluntary basis on which participants may enroll, as well as the fact that individually identifiable information connected with data will be kept confidential, will minimize the possibility of coercion and undue influence . No children will participate in this study. The participants will be asked for their understanding. The potential risks of this study will be pointed out specifically. The participants will have opportunity to ask questions at any time. The participants will also sign the consent form. All participants are expected to are proficient enough in English to understand the written consent form. This study will not involve participants who are not competent to participate in the decision making process.

CONSENT

Designer Behavior Study

Stanford University Human Subjects in Non-Medical Research Protocol ID: 10646
Protocol Director: Larry Leifer

Description You are invited to participate in a research study for better understanding the engineering design process. The duration of this study will last throughout the entire duration of the ME 310A, B, and C course sequence. During the course of this study, you will be asked passive and active participation alone and with your team. The active participation involves performing a range of tasks described:

1. A short videotaped problem discussion. In this exercise you will be asked to perform a discussion with your team members to resolve a problem within your team. The discussion will be videotaped and you will be asked to view the discussion and provide feedback about your experience of that discussion.
2. Short semi-structured interview. During each quarter of the 310 class, members of the research team will ask you for participation in short semi-structured interviews regarding your 310 project.

3. Survey. You will be asked to fill out 2 surveys regarding your 310 project experience.

To capture the different aspect this study entails the use of the following tools:

a. Ethnography with researcher observing design activity and take notes.
b. Video, audio, and other sensor based recording of your activity. *While you may be identifiable in the video clips, under no circumstance will your name be released outside of the research group.*
c. Questionnaire, where you will be requested to provide some information about your background/profile and some of your experiences and preferences.

All information collected will be kept confidential. The audiovisual recordings will not be made publicly accessible. The data from this study will be analyzed and reported in a scientific publication. The data will be anonymized before it is reported.

Risks and Benefits *The potential risk is the inadvertent release of you name to people outside of the study*. To guard against this, the research personnel have been duly instructed about the ways to prevent this from happening. The benefits which may reasonably be expected to result from this study are improvements our understanding of the engineering design process. Our strong expectation is the simultaneous improvement in the quality of products and process. In addition, we expect to develop new software tools and design methods. The data from this study will be analyzed and reported in a scientific publication. *We cannot and do not guarantee or promise that you will receive any benefits from this study***.** Your decision whether or not to participate in this study will not affect your grades in school.

Involvement Your active participation in this study will take approximately *3 to 3.5 hours per quarter.*

Payments You will receive no payment for your participation.

Subject's rights If you have read this form and have decided to participate in this project, please understand your participation is voluntary and you have the right to withdraw your consent or discontinue participation at any time without penalty or loss of benefits to which you are otherwise entitled. You have the right to refuse to answer particular questions. Your individual privacy will be maintained in all published and written data resulting from the study.

Contact information Questions, Concerns, or Complaints: If you have any questions, concerns or complaints about this research study, its procedures, risks and benefits, you should ask the Protocol Director, Larry Leifer <leifer@cdr.stanford.edu>.

Independent Contact If you are not satisfied with how this study is being conducted, or if you have any concerns, complaints, or general questions about the research or your rights as a participant, please contact the Stanford Institutional Review Board (IRB) to speak to someone independent of the research team at (650)-723-2480 or toll free at 1-866-680-2906. You can also write to the Stanford IRB, Stanford University, Stanford, CA 94305-5401.

Alternate Contact If you cannot reach the Protocol Director, please contact the research team at 650 804 4815 (Malte Jung).

- I give consent to be audiotaped during this study.
- I give consent to be videotaped during this study.
- I give consent for tapes resulting from this study to be used for analysis by specifically trained students which are not part of the main research group. All coders are trained to protect your privacy.

Signature: ____________________________ Date ________________________

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