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Methods for Assessing Epistemic Identities: Student Representations of Design and Engineering Practice

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Introduction

Traditionally, design is taught as a tool for synthesis and integration of engineering content knowledge for students in capstone courses[1]. These design courses are usually successful, in that the students often receive high marks, they come up with innovative solutions, and they are satisfied with their school experience and feel ready for the real-world. But, what is the evidence that students have actually learned and can apply their design and engineering learning successfully for synthesis and integration? What are the student's own understandings of the design process, design and engineering practice? This paper describes methods to address these questions.

Many engineering faculty report on innovative activities they do in class in support of learning. Few bolster their reports with assessments of how what they have implemented has positively enhanced student learning, nor are these activities necessarily grounded in prevailing cognitive science or educational psychology[2]. With an ultimate goal of facilitating more effective teaching and learning of design, this study proposes the development of methods to assess engineering understanding,[3] conceptions of engineering and design, and an assessment framework for design learning. For the purposes of this study we differentiate between design and engineering ways of knowing, thinking and doing (problem formulation and problem solving), and design and engineering learning (focused on change in the student's conceptual understanding of design).

Research Methods and Participants

To best address the research questions, this study uses multiple methodologies to collect and analyze data around engineering students' learning. Empirical evidence of what design and engineering thinking looks like and how it changes over time, and how students conceptualize design and engineering, comes from two participant groups: (1) a spread of undergraduate engineering students across fields of engineering, and (2) a homogeneous group of Mechanical Engineering graduate students in a project-based learning course in design and innovation for Master's students at Stanford University and.

This data collected is a jumping off point for analysis of what engineering students say about engineering and design. Evidence of how design and engineering activities change over time as well as how first-year Master's students in Mechanical Engineering conceptualize design and engineering comes from a project-based learning course ME310 Global Design Innovation[4] at Stanford University. Students were queried at the beginning, middle and end of the course for 1) a concept map of their typical design process, and 2) representations of what a designer and an engineer do at work. Both items were given out in survey form and participants answered questions by hand. Approximately 30 questionnaires were collected at each stage.

Capturing Student Definitions of 'Engineering'

The Group 1 undergraduate students were asked "In your own words, what is engineering?" as part of structured interviews undertaken during the spring quarter of their freshman year. The question was asked verbally in a one-on-one interview and participants were given as much time as needed to report their answer, giving open-ended responses. Their interviews were audio-recorded and transcribed. Participants were asked additional questions but only their responses to this particular question about defining engineering were closely examined for purposes of this paper. (The question was positioned at the very beginning of their interview so an assumption is that their answers were not primed already by other questions or responses.)

Students' engineering definition responses were open-coded looking for emergent themes that resonated across the collection of answers. A 7-part theme exposition for "what is engineering" was developed and student responses were coded and the number of categories each participants' definition encompassed was noted. Discussed later in the paper, this is summarized in Table 2.

Asking Student Notions of 'Engineering' and 'Design'

Building on the baseline responses of the undergraduate student cohort, the Group 2 cohort were asked questions to help delineate *engineering* from *design*. These students are referred to as the graduate student cohort. The graduate student participants were asked to draw both a designer and an engineer at work and define the tasks and roles that designers and engineers undertake. For years researchers have used the Draw-A-Scientist Test[5] to get at students' perceptions of that field. Based on recent work developing a Draw-an-Engineer Test[6] this paper extends the subject areas to include designers and engineers. The drawing space and task wording were repeated from Knight's[6] Draw-an-Engineer-Test protocols.

Students' representations of design and engineering were coded according to key words in their descriptions and items shown in the drawing (for example if a computer was shown or a thought bubble with a light bulb present). Emerging themes from the student Draw-a-Designer and Draw-an-Engineer tasks were extracted from this inventory.

Students Ranking Importance of Design Activities

Group 2 participants were also asked via written survey to rank-order the top 6 and bottom 6 selections from a set of design activities. As data collection and preliminary analyses were undertaken, the initial question of 'what is engineering' grew to include 'what is design.'

The list of 26 items was developed by Newstetter[7] and added to by Mosborg & Atman.[8] There were scores from 30 respondents computed, using responses from the start of the school year in fall compared to the same questionnaire collected at the end of the school year in spring.

Table 1. *List of 26 design activities.*[8] *Participants were asked to rank top 6 most important and bottom 6 least important activities.*

Abstracting	Identifying constraints	Seeking information
Brainstorming	Imaging	Sketching
Building	Iterating	Synthesizing
Communicating	Making decisions	Testing
Decomposing	Making trade-offs	Understanding the problem
Evaluating	Modeling	Using creativity
Generating alternatives	Planning	Visualizing
Goal setting	Prototyping	

Student Concept Maps of their Engineering Design Process

The Group 2 cohort was also asked to “Draw your typical design process.” Models of design are prevalent in textbooks and literature.[9] In action however, design practitioners often synthesize and adapt their own experiences and learning into a mental model of their design process. Mosborg[10] examined the design process representations of 18 expert design practioners in an effort to get at one universal version. Previous studies[11 12] have characterized the relative design processes of college freshman and seniors, design educators and practicing designers. Based on individuals constrained (both by time and scope of problem) in a lab design activity, Atman et al. were able to identify and describe differences in design process practice, namely, time on problem definition, chronology of process, and iterative steps.

Adams[13] described a possible design expertise continuum from novice to expert. An open question from this work is investigating the trajectory of individual student learning (Figure 2) in Design Thinking.

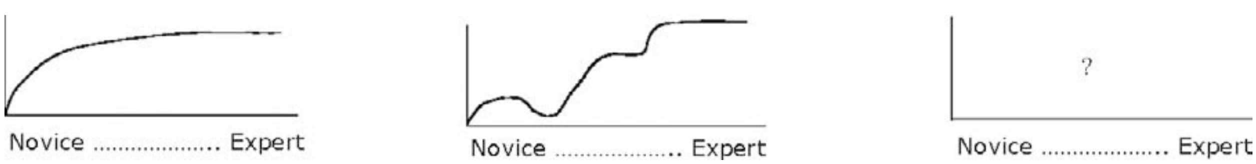

Figure 2. *Potential Shapes of the Design Thinking Learning Trajectory, from Adams* [13]

Adams[14] found novice designers followed a waterfall pattern and more expert designers were more liable to skip around the design process steps. By asking students to draw their “typical design process” it was hoped that the authors could capture or approximate the students’ mental model.

Figure 3 shows an example of a linear design process gathered from a Group 2 student at the start of the graduate design and innovation course.

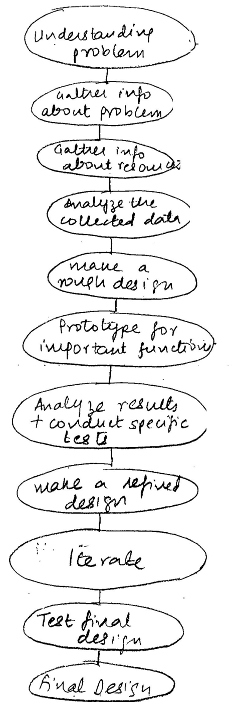

Figure 3. *Example of a student's linear design process concept map*

Results

Student Definitions of 'Engineering'

The array of Group 1 student responses to "In your own words, what is engineering" were parsed and separate concepts within each answer were identified. Eight categories of themes emerged: apply, science, math, quality, world, stuff and design (these categories are listed in Table 2). In part, the categories are incomplete; in total they encompass a full straw man definition for engineering: *an application of science and math to quality of life, to solve problems of the world by making stuff by design.* Table 3 highlights example student responses to add context to this analysis. The number of qualifier themes (out of eight) mentioned in the students' response is also noted.

Table 2. *Themes of students' engineering definitions. Students were asked 'In your own words, what is engineering?'*

Themes	*Labels*
an application	apply
of science	science
of math	math
to quality of life	quality
to solve problems	solve
of the world	world
by making stuff	stuff
by design	design

Table 3. *Example student responses to 'In your own works, what is engineering?'*

Example A
"I would call engineering the application of math and scientific concepts to solve real work problems through creating technologies."
scored 6 of 8 qualifier themes

Example B
"basically like technical problem solving..."
scored 2 of 8 qualifier themes

Example C
"Engineering solves problems people face in the real world."
scored 2 of 8 qualifier themes

Of the 30 responses, many were partial answers in regard to the total eight themes. The distribution of number of qualifier themes per response and frequency are shown in Figure 4. Almost two-thirds of respondents only focused on one or two of the eight thematic categories identified.

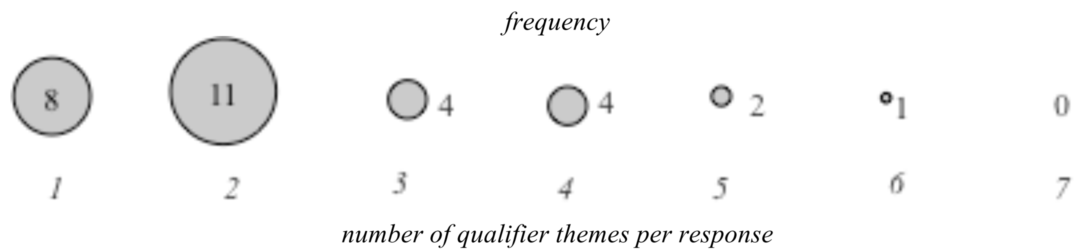

Figure 4. *Distribution of number of qualifier themes from individual responses.*

Student Notions of 'Engineering' and 'Design'

Based on drawing tasks collected from Group 2 participants, a student-based distinction came from the analysis. Figure 5 shows student representations of the Draw-a-Designer-Test and Draw-an-Engineer-Test.

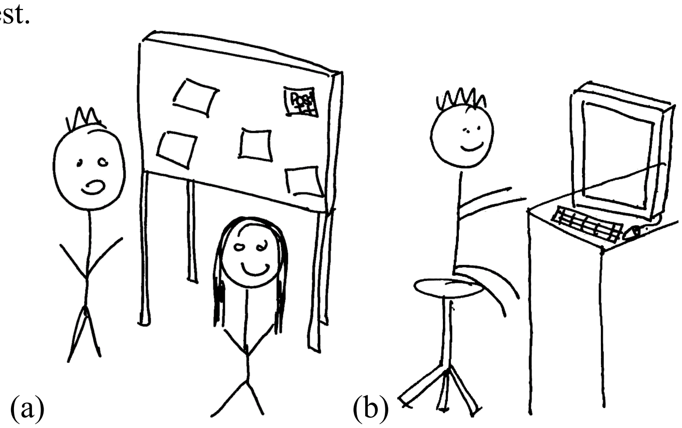

Figure 5. *Examples of (same) student representations form the (a) draw-a-designer-test and (b) draw-an-engineer-test*

Students involved in design and engineering practice consider the roles and responsibilities of designers and engineers to be distinct but complementary. Along two themes: 1) designers come up with ideas and engineers implement them, and 2) designers talk to users and engineers work on computers. The delineation between these roles has been both curious and surprising and gives support to distinction between design and engineering activities.[15]

Ranked Importance of Design Activities

Aggregate rankings of Group 2 students' appraisals of most and least important design activities were calculated. This information is shown in Table 5.

It is interesting to note that the top 5 and bottom 5 largely remain similar measured at the start of the course and end of the course. For the MIDA (most important design activities), iteration rose from rank #5 to rank #1. Other MIDAs then were Prototyping, Understanding, Brainstorming and Communication. For LIDA (least important design activities), Abstracting, Decomposing, Imagining and Making tradeoffs were present both at the start and end; Building and Visualizing dropped out and Goal setting and Modeling appeared over time.

Table 5. *Summary of most and least important design activities question responses*

Most important design activities

At the start of the course	*At the end of the course*
1. Prototyping	**1. Iterating**
1. Understanding	2. Prototyping
3. Brainstorming	3. Understanding
4. Communication	3. Brainstorming
5. Iterating	5. Communication

Least important design activities

At the start of the course	*At the end of the course*
1. Abstracting	1. Abstracting
2. Decomposing	2. Decomposing
3. Building	3. Making tradeoffs
4. Imagining	3. *Modeling*
5. Making tradeoffs	5. Imagining
5. *Visualizing*	5. *Goal setting*

Student Concept Maps of their Engineering Design Process

Figure 6 captures an example of a student design process model from the end of the course. This general trend towards a more complex and flexible representation, even of an iterative nature of the design process steps, was the norm among participants.

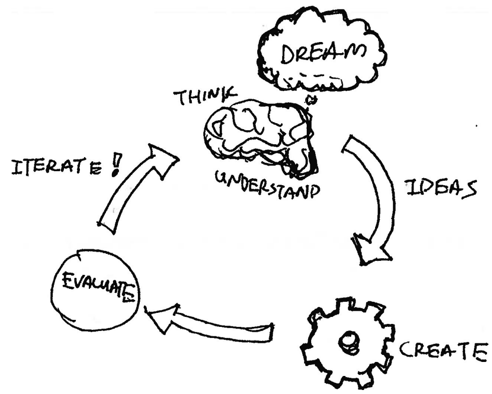

Figure 6. *Example of a student's circular design process concept map*

The results indicate that there is a learning trajectory of student concept maps of design process from a simple, linear representation to more involved circular and iterative models. What does a design process of a student learning look like at the beginning and end of a design experience?

Based on empirical work and learning theory, the authors propose a spectrum of cognitive mental models or possible representations of the design process inclusive of design thinking and engineering doing that advances from novice to intermediate to expert. Novice designers first report concept maps of the design process in Linear (horizontal or vertical) fashion. Connections made to the Circular nature or Successive nature of the design process creates maturing models. Advancement to the appreciation of the Iterative nature of the design process is where most student designers get to during their education. Neeley[16] developed a framework for adaptive expertise that represents the way that the industry expert designers behave where the design process evaporates and the expert uses the normative design steps as an interwoven number of possible tools to apply strategically. Also based on the author's pilot studies of students in the ME310 course during the 2007-2008 school year (and subsequent dissertation work[3, 16]), we present 5 distinct ideal models of the design process as steps in a student's Design Thinking learning trajectory in Figure 7. Using this taxonomy, students' maps can be classified as one of the ideal models of the design process shown.

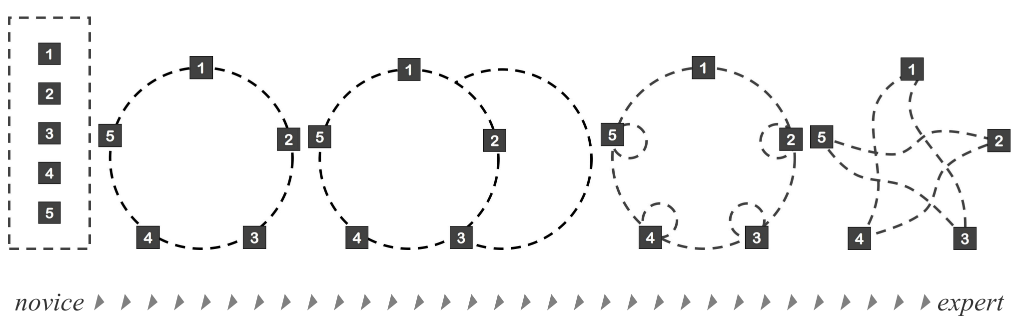

Figure 7. *Models of the Design Process as Steps in a Student's Design Thinking Learning Trajectory; from novice to expert, (l-r) , linear , circular, successive, iterative, interwoven*

Future Work

So, how do students learn and re-learn design thinking? The authors hypothesize that students learn and re-learn design thinking and the design process by doing authentic activities in project-based learning courses similar to the course Group 2 participants were engaged in. Students learn and re-learn design thinking through the act of repeatedly experiencing a design process coached by the teaching team, with each iteration improving on their procedural skills and synthetic knowledge to create anew. The design process serves as a cognitive apprenticeship[17]; each constructive design activity and design experience, through interaction with teammates or coaches, gives students opportunities to refine their model of design and design practice. Each interaction taken under the guise of a step in the design process helps the learner compare and contrast to their own mental model and forces the learner to clarify and rectify their model with their experience. Repeated design experiences serve to advance the student's model of design thinking and the design process.

What specific experiences during the design process help accelerate or impede a student's design learning? Anything that questions the student's model of the design process forces a rectifying of the mental model and learning happens; through iterations the student can continually refine the cognitive mental model as measure of design competency. In project-based learning environments, ambiguity abounds and in a state that lacks certainty students often fumble at what their next step is, using their own developing judgment and sense of self efficacy to move forward.

We hypothesize that both the breadth and frequency of iterative steps in the design process give students more learning moments to apply their model of the design process, helping to rectify misconceptions and realign their mental model of their design process. The author is building on preliminary observations of student design activity and learning in ME310 and a pilot study of a qualitative content analysis of student design documentation from past years.[18] The basic pedagogical approach as evidenced by course assignments and milestones to teaching design in the ME310 course is comparable to the iterative ideal design process model. Students are primed 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[19] fixation on ideas[20] and solution focusing.[21] By way of situated qualitative design observation these and other phenomena will be captured and analyzed as emerging themes from design activities.

Impact

By examining the engineering students' learning experience through the lens of cognitive science and establishing a framework for assessing the Design Thinking Learning Trajectory, this work can impact the quality of design teaching and inspire industry to offer methodologies to mediate multi-disciplinary collaborations. Coming to understand (*scholarship of merit)* and promoting the efficacy of project-based learning and design thinking (*scholarship of impact*)[22] are the expected results of this project.

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