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Appraising Student Design Learning: Comparing Design Processes of First-year and Senior-year Engineering Students

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Introduction

Traditionally, engineering design is taught as a tool for synthesis and integration of engineering content knowledge for students in capstone courses (Todd, Magleby, Sorensen, Swan & Anthony, 1995). These engineering design courses are usually successful, in that the students do well, 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 and engineering design practice? How might they conceive of their own engineering and design epistemic identities? This work investigates 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 (Newstetter, Eastman, McCracken & Michael, 2001).

With an ultimate goal of facilitating more effective teaching and learning of design, this study proposes the development of methods to assess engineering understanding (Lande & Leifer, 2009), 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).

Literature Review

Model of Design Process

We are interested in students doing an activity "Draw your typical design process." Models of design are prevalent in textbooks and literature (Dubberly, 2010). In action however, design practitioners often synthesize and adapt their own experiences and learning into a mental model of their design process. Mosborg, Adams, Kim, Atman, Turns & Cardella (2005) examined the design process representations of 18 expert design practioners in an effort to get at one universal version. Previous studies (Atman, Cardella, Turns & Adams, 2005; Atman, Turn, Cardella & Adams, 2003) 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. (2005) were able to identify and describe differences in design process practice such as time on problem definition, chronology of process, and iterative steps.

A Design Expertise Continuum

Adams, Turns, & Atman (2003) 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 1) in Design Thinking.

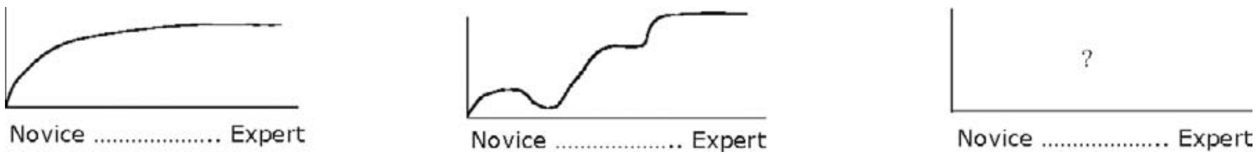


Figure 1. *Potential Shapes of the Design Thinking Learning Trajectory, from Adams* [13]

Adams (2001) 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.

Classifications and Learning Trajectories

The general coding scheme is based on a spectrum of students' models of the design process. This has been explored in previous, related work of one of this paper's authors (Lande & Leifer, 2009; Lande, 2009; Lande, 2018, Lande & Liu, 2019; Lande, 2020). Steps in a student's design thinking learning trajectory, from novice to expert, is demonstrated by, linear, circular, successive, iterative, interwoven, and affective concept maps, as illustrated in Figure 2 below.

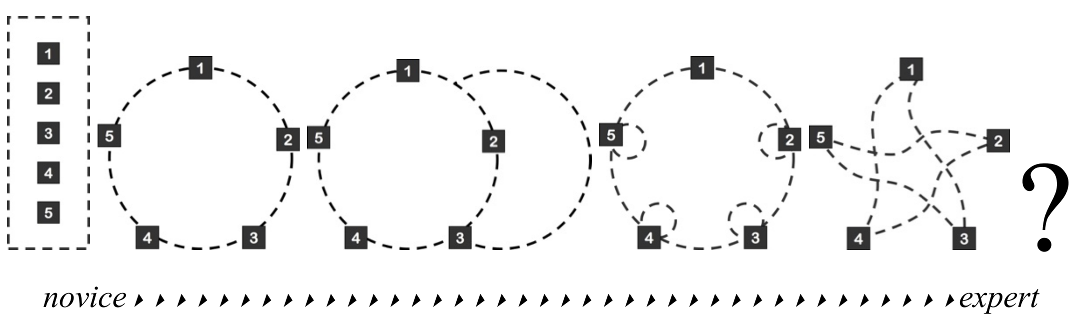


Figure 2. *Models of the Design Process as steps in a Design Thinking Learning Trajectory; from novice to expert, (l-r), linear, circular, successive, iterative, interwoven, affective. (adapted from Lande, 2019)*

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. Also based on author's studies of students in a mechanical engineering design course these distinct ideal models of the design process as steps in a student's Design Thinking learning trajectory are shown in Figure 2. Using this taxonomy, students' maps can be classified as one of the ideal models of the design process shown.

Neeley (2007) 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.

This research effort is part of a larger research project to explore and understand the learning trajectories of students and their learning gains in the product-based learning, undergraduate engineering classroom. The notion of learning trajectories (here applied to engineering learning) is borrowed from mathematics education (Lande and Liu, 2018). By identifying and exploring a typology of design process concept maps we can offer sets of "design learning trajectories" over time. We explore how novices' and experts' mental models of an engineering design process come into being and evolveß through educational experiences. 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, as shown above in Figure 2. Additional efforts by the authors have been to specifically explain the research basis of the learning trajectories concept (Lande and Liu, 2018, Lande Liu, 2018). A summary paper on these research efforts is to be published contemporaneously (Lande, 2021).

Research Methods and Participants

To best address the research questions at hand, this study uses student drawing of their design process to collect and analyze data around engineering students' learning. Empirical evidence of how students conceptualize design and engineering, comes from two participant groups: (1) first year mechanical engineering students in their first semester, in ME 110 Introduction to Mechanical Engineering course, and (2) senior mechanical engineering students in an elective course ME 465 Design Thinking and Innovation for Mechanical Engineers course. Both participant groups are students at [university]. The Introduction to Mechanical Engineering course provides an overview of general engineering topics such as the engineering profession, units and unit conversion, the engineering design process, technical problem solving and communications, as well as mechanical engineering specific topic areas such as forces in structures and machines, materials and stresses, fluids engineering and thermal systems. Individual class sessions include hands-on design and building activities to support the engineering design or engineering science content. Students also have a number of substantial design project challenge experiences over the course of the semester. The senior cohort of students is in an optional senior elective that augments their engineering design experiences (foundational product development through capstone design) with introduction of a human-centered design approach to get at latent and expressed needs for problems where people are at the center of the problem and solution space. Similarly a problem-based learning approach is taken and students have many in-class hands-on activities to support different aspects of human centered design (like empathy exercises and rapid prototyping activities) as well as longer-form design challenges over the semester.

Students were queried at the beginning and end of the course for 1) concept map of their typical design process, and 2) conceptions of engineering and design. Approximately 30 questionnaires were collected at each stage.

Students were asked to draw their "typical design process." Models of design are prevalent in textbooks and literature. Once in action though, design practitioners often synthesize and adapt their own experiences and learning into a mental model of their design process. Study of novice and expert designers has generated insight into these. By asking students to draw their *typical design process* it was hoped that the authors could approximate the student's mental model.

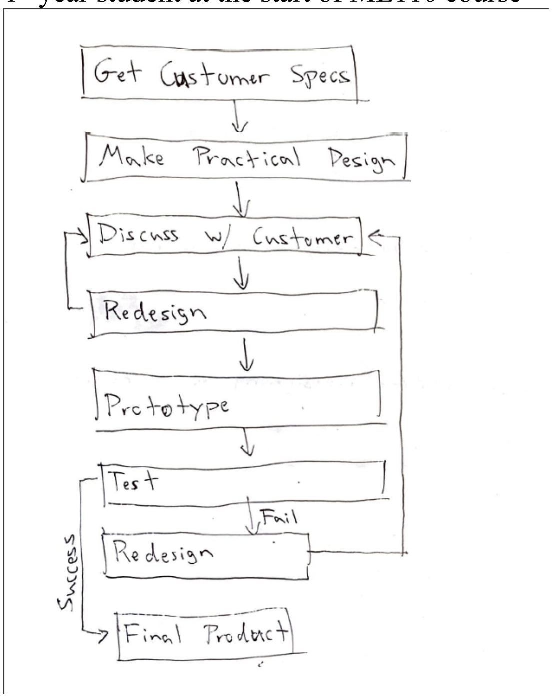
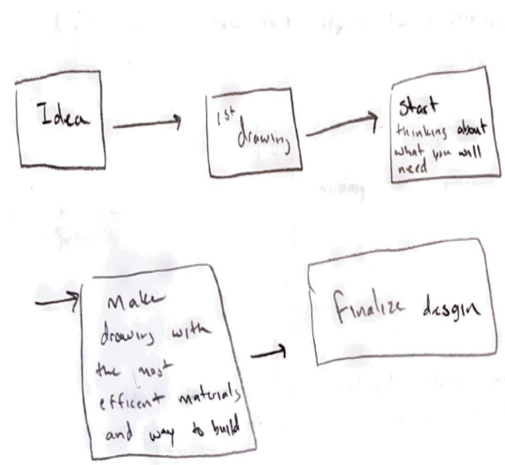
After student design process maps were collected, these process maps were then scanned, and data was collected from each class using multiple passes to create the data graphs seen in the results section of this paper. The first pass was to look at each student and identify how many steps they used in their design process at both the beginning and the end of the semester for both the first-year students and senior students. This approach can show how detailed the students' design process was and how it had changed over the course of a semester. The second pass was to identify common language used throughout the different diagrams to see how the students picked up on words or phrases to form their idea of the design process from their course work. The last method used a learning trajectory map from previous work to put the students on a spectrum from novice to expert in the design process to see how they grew over a semester.

This process was then repeated at the end of the semester with the same two classes to track any changes to the students maps after post course experience.

Results

Student concept maps were collected, examples shown below in Figure 3. Figure 3 shows example concept maps from both groups of students at the beginning and end of the semester.

Using the methods described above, the collections of design process concept maps could then be further analyzed qualitatively, word usage transcribed, into the tables and figures below. The interpretation of these tables and figures will be discussed in the finding portion of this paper.

<table>
<tr><td></td><td>1st year student</td><td>senior student</td></tr>
<tr><td>pre</td><td>1st year student at the start of ME110 course

</td><td>senior student at the start of the ME 465 course

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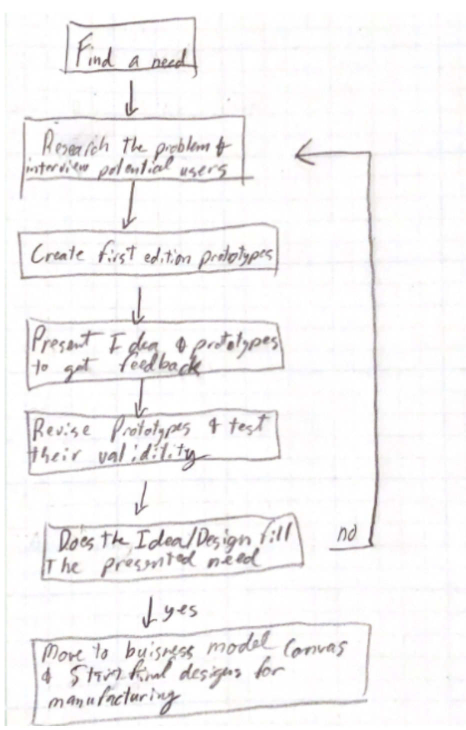
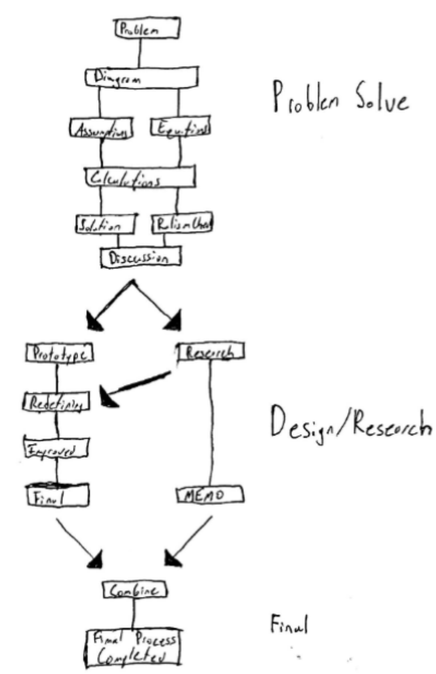
<tr><td>post</td><td>1st year student at the end of the ME110 course

</td><td>senior student at the end of the ME 465 course

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</table>

Figure 3. Example Student Design Process Concept Maps

Table 1 lists and Figure 4 is a visual snapshot that compares the number of steps the students had in their maps at the beginning and the end of the semester.

Table 1: Number of steps in design process concept maps

1st year students

#	PRE (n=25)	POST (n=15)
3	1	0
4	1	0
5	6	3
6	6	2
7	5	2
8	1	4
9	4	1
10+	1	3

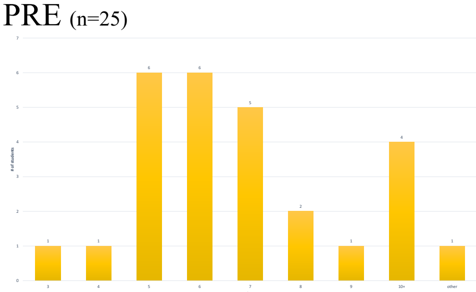
senior students

#	PRE (n=23)	POST (n=17)
3	2	0
4	0	0
5	8	3
6	4	7
7	1	3
8	4	3
9	1	1
10+	2	0
other	1	

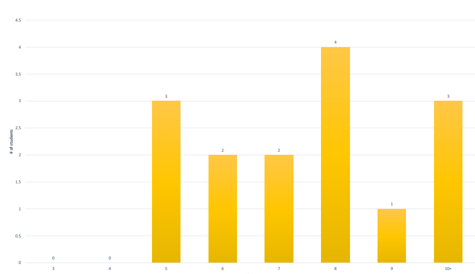
Figure 4: Graph visualizations of steps in design process concept maps

1st year students

PRE (n=25)

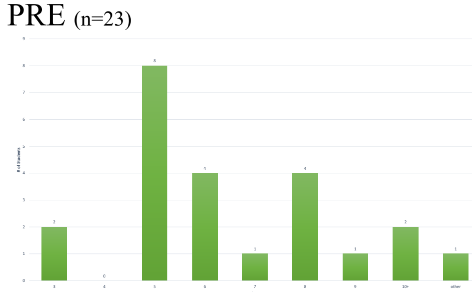


POST (n=15)



senior students

PRE (n=23)



POST (n=17)

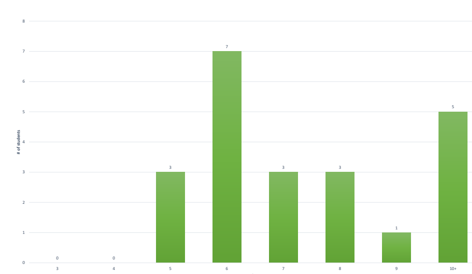


Table 2 lists the common language picked and used by the students of both the first-year ME 110 and senior ME 465 class as the semester progressed.

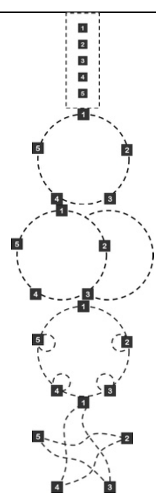
Table 2: Language used in design process concept maps (# instances)

1st year students			*senior students*		
concepts	PRE (n=25)	POST (n=15)	concepts	PRE (n=23)	POST (n=17)
problem		11	*problem*	20	18
brainstorm	21	13	*brainstorm*	17	17
research	5	7	*research*		14
prototype	16	12	*prototype*	14	20
failures		4	*failures*		
test	16	12	*test*	11	14
finalize	15		*finalize*	10	15
repetition	9	10	*repetition*	13	19
improve		8	design	8	9
solution		12	feedback	12	
			redesign	8	11

Figure 5 compares the first-year students to the seniors on how they placed on the spectrum of learning trajectories (as illustrated in Figure 2).

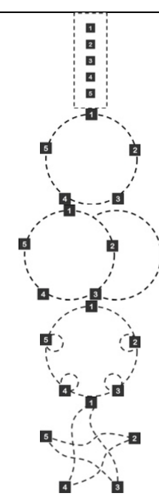
Figure 5. Comparing first-year students (ME 110) and senior students (ME 465)

1st year students



spectrum:	(n=27)
1 – novice	10
2	10
3	5
4	-
5 – expert	-
other	2

senior students



spectrum:	(n=23)
1 – novice	5
2	8
3	8
4	-
5 – expert	-
other	2

Findings

Expected

From the results there many observations that can be made. Some observations were to be expected from previous research and knowledge of the subject while other results generated unexpected surprises to the research. Things that were noticed were that the first-year ME 110 students took in and changed their process more than the senior ME 465 students as a result of completing the ME 110 course. The other thing that was noticed with the both the first-year ME 110 and senior ME 465 students is that the experience that each student had prior to entering the classes help shape and mold their initial process map. Some of the first-year ME 110 students had high school experience with engineering and many of the seniors had internship experience as well as experience from another class or extracurricular activities that have their own design process to follow.

Of the observations made during the research many of them were not surprising and expected results. These included the following. The senior ME 465 students didn't have much change in their design processes from the beginning to the end of the semester. This wasn't surprising since they had already spent their entire academic career forming this process through other classes and personal experiences. The other not surprising thing with the senior ME 465 students is that they came in with more general knowledge of the design process than the incoming freshman with little to no engineering background. This means that during their time at [university] they did pick up the necessary knowledge of the design process to advance academically. This led them to placing higher on the learning trajectory spectrum than the freshman did, at an intermediate point where the freshman sit at novice even at the end of the semester.

Surprising

There were observations that were surprising results to the research. When the first-year ME 110 students made their process maps at the end of the semester their language shifted from personal vague language to a common engineering language that was picked up in the classroom. It could also be seen that by the end of the semester the first-year ME 110 students adapted to a more iterative process than the linear process that most of them started out with. This led them to rank higher on the spectrum then they did originally. By the end of the semester both the first-year ME 110 and senior ME 465 students also increased the number of steps they had in their process and the maps went into more detail of steps using that common language previously mentioned.

Conclusions

From the research and the data collected during that time a few conclusions can be drawn. The first is that students entering the mechanical engineering department as a freshman compared to when they prepare to leave the school after graduation their knowledge of the design process has grown to reflect what they have learned over their education. Another conclusion is that it is important to teach the steps to the design process to the students as first year students when it is easy for them to pick up common language and adapt their way of looking at the design process. This is evident by comparing the language graphs in the results section of this paper. The Seniors did not show as much change in their process as the freshmen did. This implies that by the time students reach their last year of education, they already have all the tools to put together a map of the design process based off of education and supplemented with personal experience. The final conclusion that was drawn is that by the time of graduation, mechanical engineering students are not yet experts in the design process according to the learning trajectory spectrum used during research. This leads to new question and new research potential for the future to see at what point one becomes an expert in the design process.

Next Steps and Future Work

From the research that has been complete, new questions were raised that need answers. The team would like to continue to look at education curriculum at [university] and see the design process from the eyes of a second- and third-year student to compare to that of the freshman and senior to see at what points all the pieces of the design process come together. We would also like to look at the instructors/professors version of the design process to see how that affects their students' design processes.

Faculty, as well, have (more developed) models for engineering design activity. In addition, textbooks can capture and reflect yet another set of prescriptive and descriptive design models that can be propagated within courses, across curricula, and across institutions. Negotiating these many representations may be aligned or misaligned with the intended learning experience. Within our undergraduate mechanical engineering program, we are trying to make explicit (for students and faculty alike) the local set of engineering design process models embedded in our courses and curriculum as reflected by the stakeholders and resources involved. The intent is to align the process-specific content knowledge across these courses and student experiences. We are collecting student and faculty design process concept maps from foundational, mezzanine, and capstone design courses, and undertaking analysis of those. We are also appraising resources like textbooks across the program. In total, we are starting to capture a variety of existing and used models for engineering design process employed locally, both implicitly and explicitly related to the intended formal and informal learning environments.

We are interested in how what we can gather from student reflections on their design process can inform how we teach and how students develop their knowledge and practice of the engineering design process. For mechanical engineering students, the engineering design process is a foundational aspect to how they come to learn and apply their problem finding and problem solving work. While there is a range from novice to expert across the implementation and application of the engineering design process, we find it most interesting to follow that development over time. How they represent a professional practice of mechanical engineers can be a proxy for what student know. The conceptualization of the engineering design process can project their epistemic, or knowing, within their field of study. Future work can explore the mapping of their design process knowledge to their identity as student engineering and future engineers.

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