

## **Board 87: Design Process Geometries: Shapes and Learning Trajectories of Engineering Students' Design Process Concept Maps**

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## **Introduction**

In our ongoing exploration of this EAGER EEC NSF-funded project, we share results of the design concept maps part of our research project. This paper is intended to share formative development of a coding scheme to assess and evaluate drawings by undergraduate engineering students of their engineering design process. There is a spectrum of student responses and developing a taxonomy, or categorization, is helpful to better understand where students begin and end from a design project learning experience. This can then inform and illustrate the ways in which students balance breadth and depth and learn and apply their engineering know how.

Design may appear throughout a curriculum or be substantiated as a capstone experience for the synthesis and integration of prior engineering content knowledge [1]. It may have implication on the disciplinary approach to teaching and learning, as well as how different educational experience and interventions in the classroom may advance learning. With an ultimate goal of facilitating more effective teaching and learning of design [2], 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).

## **Making Thinking Explicit through Concept Maps**

Models of design are prevalent in textbooks and literature [4]. Once in action though, design practitioners often synthesize and adapt their own experiences and learning into a mental model of their design process. Engineering students demonstrate their design prowess and design learning through either the creation of an artifact, or the documenting and reflection on their engineering design process, or some combination of these. As design educators search for a means to understand and evaluate what design learning may more faithfully look like, the notion of a spectrum of varying types and representations of individual students' design process understandings has arisen. Design textbooks present models for the engineering design process. Often it is clear, rectified steps and connections of how the engineering design process may manifest itself in engineering design activity.

Hugh Dubberly has collected more than 100 visual representations of concept maps from both textbooks and industry [4]. He lists the components as to "create a matrix showing the relations of terms" [5]. The resulting compendium of concepts maps for the design process then is a resource that indicates the unique mental models from education or practice. For example, in Figures 1 and 2 see an example from the Pahl and Beitz textbook, and the design process propagated by the Stanford d.school:

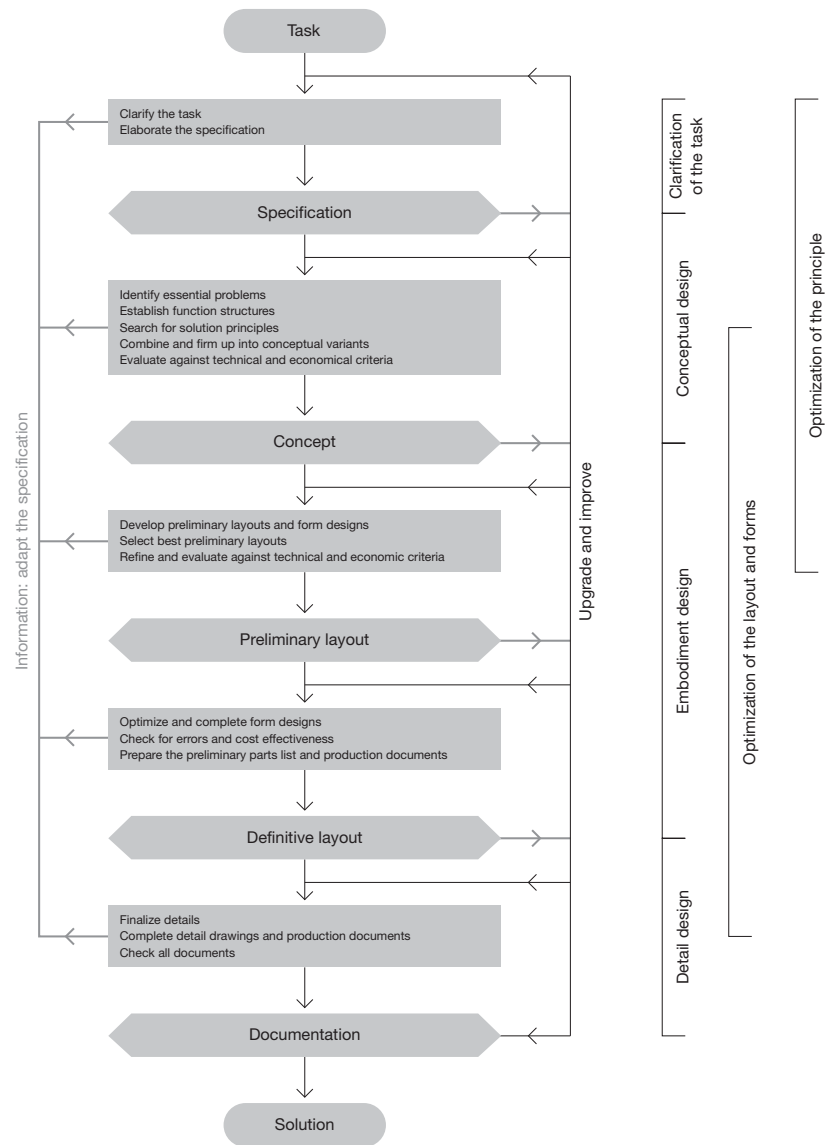


Figure 1: Pahl and Beitz from [4]

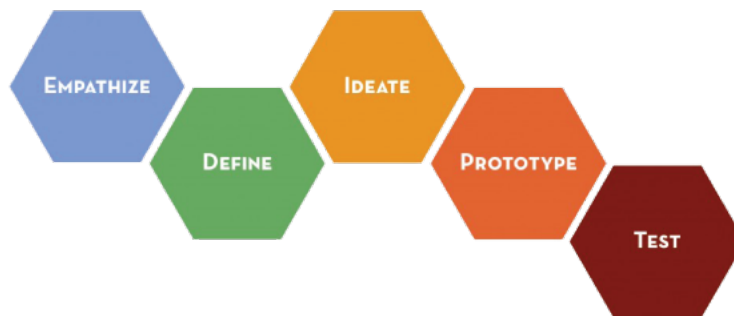


Figure 2: d.school design process model

Mosborg [6] examined the design process representations of expert design practitioners in an effort to get at one universal version. Previous studies [7, 8] 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.

Additional work [9] 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 3) in Design Thinking. This asks a foundational question of what learning trajectory, or how many learning trajectories, may a learner or practitioner experience and how they are supported.

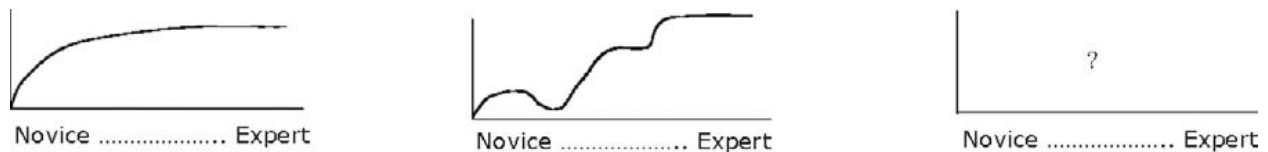


Figure 3 Potential Shapes of the Design Thinking Learning Trajectory, from Adams [14]

Adams [10] 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.

### **Methods: Draw Your Design Process**

The research questions for this larger research project are about how engineering students demonstrate learning through their practices and their thinking. Constrained to the idea of mental models reflected through such concept maps for the engineering design process, and how it may change from before a specific learning experience, to after, this focused study relies on the collection and analysis of those to indicate learning more broadly.

First-semester students in courses are asked to complete a short questionnaire asking them to “Draw your making process.” Maps were collected and classified along the spectrum and developmental range of the student design learning continuum (Figure 6). A subset of students are to be selected to review their maps and perform talk alouds to elucidate further descriptions and reasoning within their process.

Through a collection of undergraduate engineering students’ drawings of their design process, we use a qualitative approach to code students’ sketches of their engineering design process to extract a generalizable model for design learning. Documented at the start and end of a number

of courses, we conduct analysis of these as concept maps. Through established methods to analyze concept maps as tools for scientific learning, we identify topics as “nodes,” directionality connecting through “links” and patterns more generally connecting within. The former may be readily identified as design process steps, the latter as indications for iteration.

### Student Examples

Figure 4 shows an example of a linear design process from a student at the start of the mechanical engineering design course.

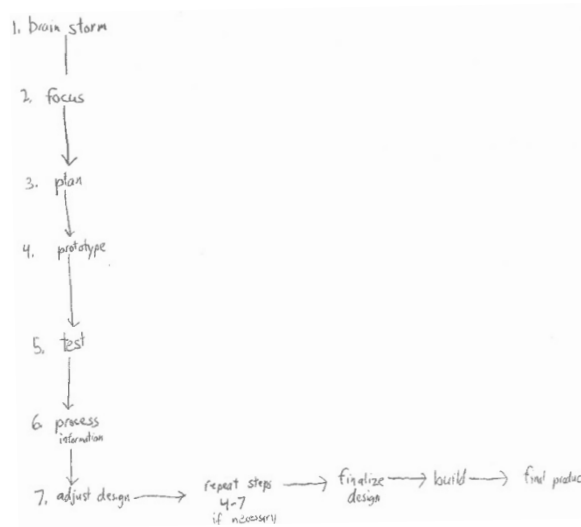


Figure 4 Example of a student’s linear design process concept map

Figure 5 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.

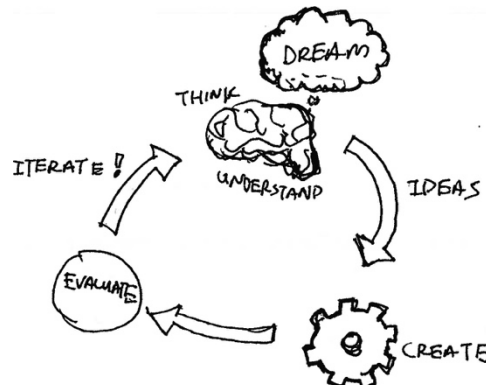


Figure 5 Example of a student’s circular design process concept map

## Classifications and Learning Trajectories

The general coding scheme is based on a spectrum of students' models of the design process. 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 6 below.

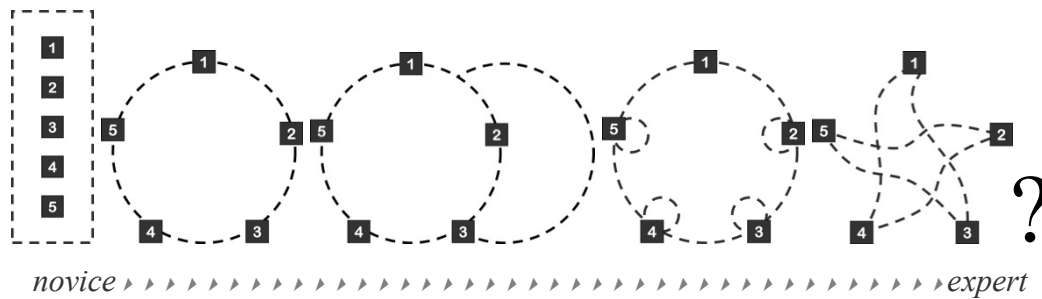


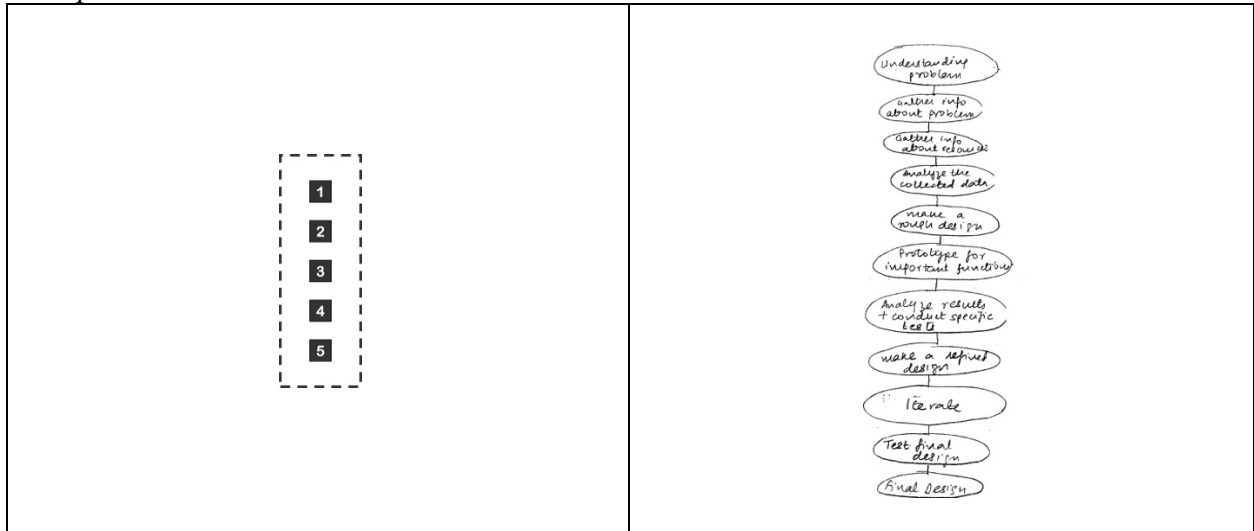
Figure 6: Models of the Design Process as steps in a S Design Thinking Learning Trajectory; from novice to expert, (l-r), linear, circular, successive, iterative, interwoven, affective.

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 [11] 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.

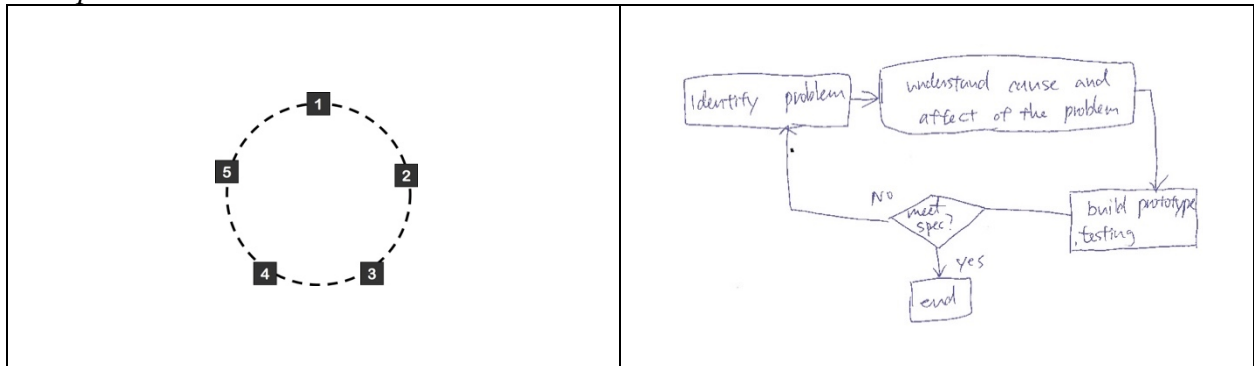
Also based on author's pilot studies of students in a mechanical engineering design course we present distinct ideal models of the design process as steps in a student's Design Thinking learning trajectory in Figure 3. Using this taxonomy, students' maps can be classified as one of the ideal models of the design process shown.

# Student Examples

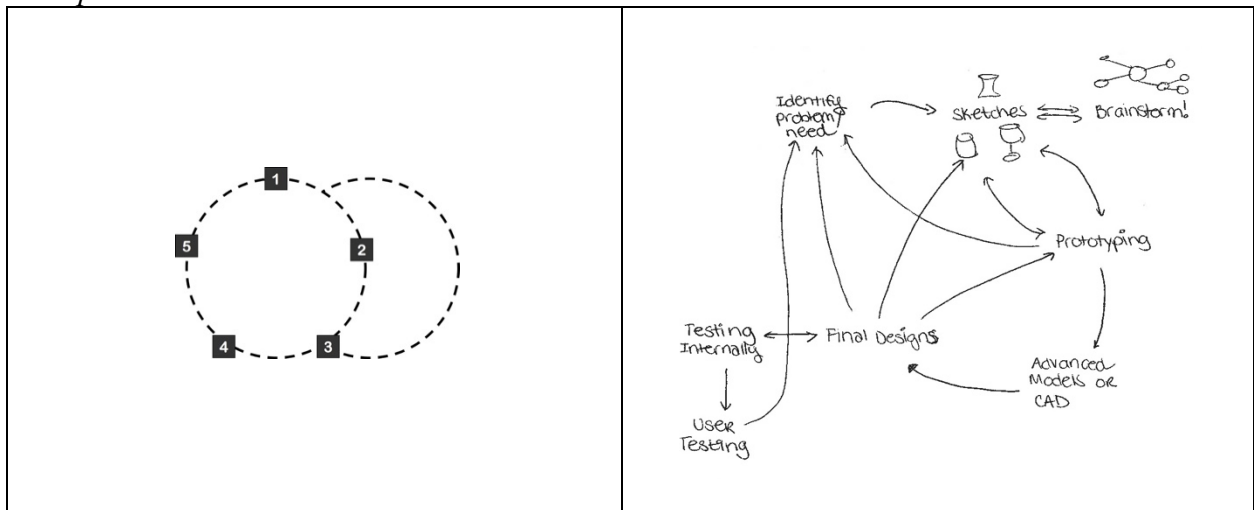
## Examples: Linear



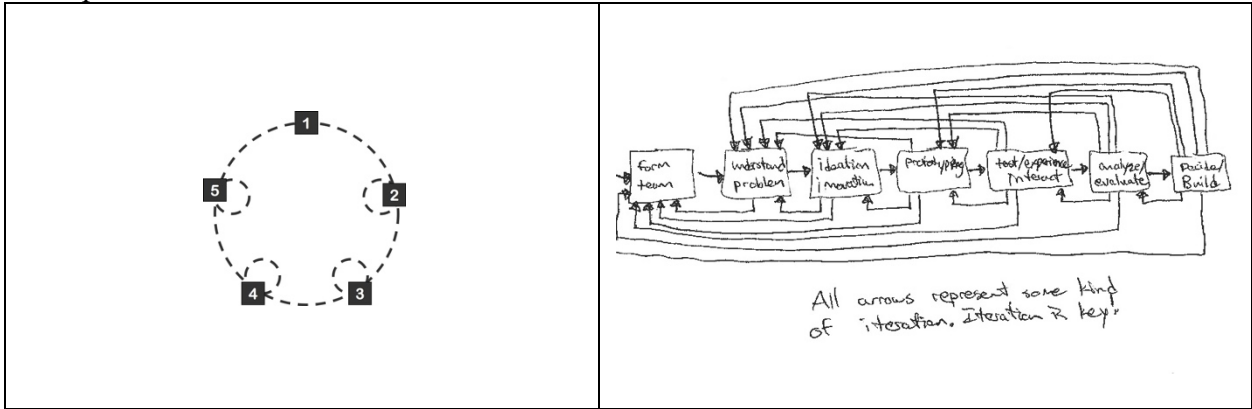
## Examples: Circular



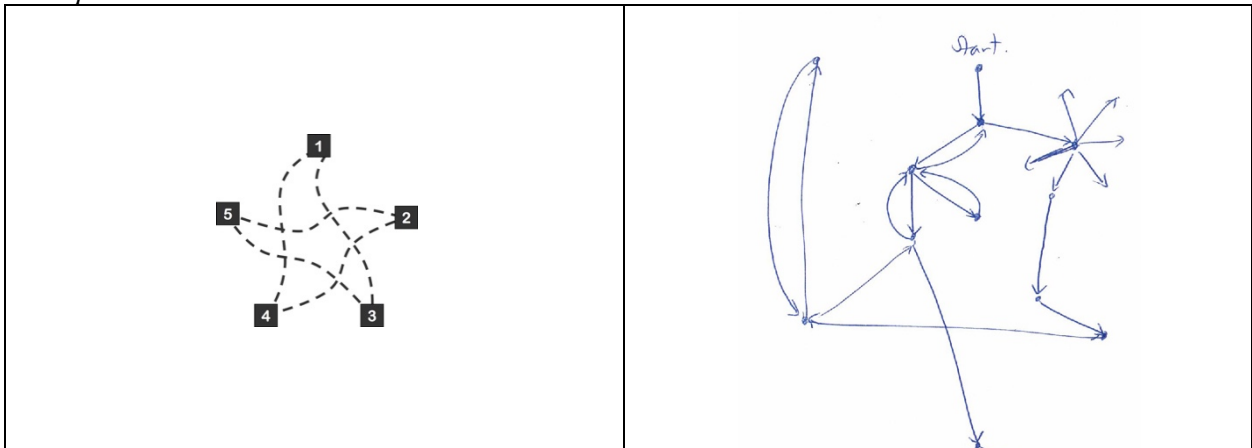
## Examples: Successive



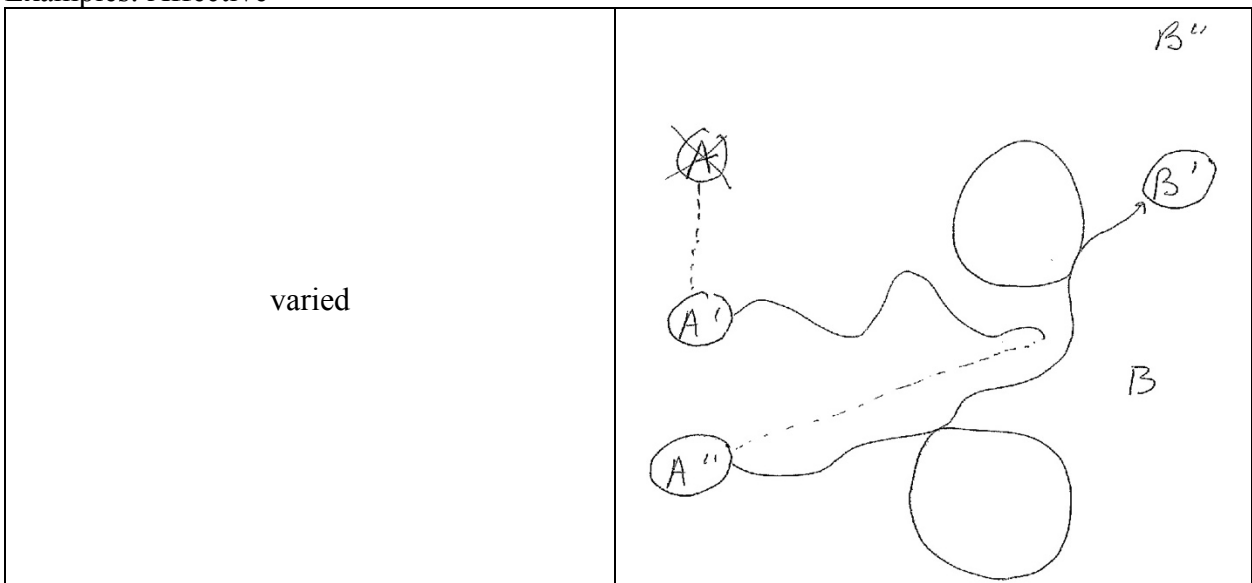
Examples: Iterative



Examples: Interwoven



Examples: Affective





## **Design Cognition**

We explore the patterns and procedures of the engineering design and learning process, grading patterns as generally being linear, circular, successive, and adaptive. This is reflected through cognitive knowledge types and design expertise, specifically when and how declarative, procedural and strategic knowledge are used. This work presents this approach as “Design Process Geometries” as a means to examine individual’s design learning process in two dimensions: internally, how an engineering undergraduate shift between declarative, procedural and strategic knowledge when they make design decisions; externally, how this design learning process can be represented in a visual form.

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 comes into being and evolves 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.

## **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 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 [12]; 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 [13]. 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 authors are building on preliminary observations of student design activity and learning in a mechanical engineering design course and a pilot study of a qualitative content analysis of student design documentation from past years [20]. The basic pedagogical approach as evidenced by course assignments and milestones to teaching design in the 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 [13], fixation on ideas [14], and solution focusing [15]. 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*) [16] are the expected results of this project.

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## **References**

1. Todd, R.H., Magleby, S.P., Sorensen, C.D., Swan, B.R., & Anthony, D.K. (1995). "A Survey of Capstone Engineering Courses in North America." *Journal of Engineering Education*, Vol. 84, No. 2, pp. 165- 174.
2. Newstetter, W.C., Eastman, C.E., McCracken, W.M. (2001). "Bringing Design Knowing and Learning Together" in *Design Knowing and Learning: Cognition in Design Education*.
3. Lande, M. & Leifer, L. (2009). Student representations & conceptions of design & engineering. *Proceedings of Frontiers in Education conference*. San Antonio, TX.

4. Dubberly, H. Innovation Models, prepared for the Institute for the Creative Process, Alberta College of Art and Design. Retrieved from <http://www.dubberly.com>.
5. Dubberly, H. (2010). Creating Concept Maps. Dubberly Design Office. Retrieved from <http://dubberly.com>.
6. Mosborg, S., Adams, R., Kim, R., Atman, C., Turns, J. & Cardella, M. (2005). Conceptions of the Engineering Design Process: An Expert Study of Advanced Practicing Professionals. Proceedings of American Society for Engineering Education Conference. Portland, OR.
7. Atman, C.J., Cardella, M.E., Turns, J. & Adams, R. (2005). "Comparing freshman and senior engineering design processes: an in-depth follow-up study." *Design Studies*, 26(4).
8. Atman, C.J., Turns, J., Cardella, M.E. & Adams, R. (2003). "The Design Processes of Engineering Educators: Thick Descriptions and Potential Implications." Design Thinking Research Symposium VI Proceedings, Sydney, Australia.
9. Adams, R., Turns, J. & Atman C.J. (2003). "What could design learning look like?" Proceedings of the Annual Design Thinking Research Symposium VI, Sydney, Australia.
10. Adams, R. (2001). Cognitive Process in Iterative Design Behavior. Dissertation (Ph. D.) University of Washington.
11. Neeley, W.L. (2007). Adaptive Design Expertise, Stanford University Dissertation, 2007.
12. Collins, A., Brown, J.S. & Newman, S.E. (1987). Cognitive apprenticeship: Teaching the craft of reading, writing and mathematics (Tech. Rep. No. 403). Champaign: University of Illinois at Urbana-Champaign, Center for the Study of Reading.
13. Bucciarelli, L. (2004). *Designing Engineers*. MIT Press, Cambridge, MA.
14. Jansson, D. G. & Smith S.M. (1991). Design Fixation, *Design Studies*, 12(1).
15. Lloyd, P. & Scott, P. (1994). Discovering the Design Problem. *Design Studies*, 15(2).
16. Lande, M., Adams, R., Chen, H., Currano, R. & Leifer, L. (2007). "Scholarship of impact" framework in engineering education research: Learnings from the Institute for Scholarship on Engineering Education. Proceedings of Frontiers in Education. Milwaukee, WI.