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Learning Trajectories Through Undergraduate Engineering Curricula and Experiences

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This NSF EEC EAGER research project investigates how undergraduate engineering students' learning trajectories evolve over time, from 1st to senior year, along a novice to expert spectrum. We borrow the idea of "learning trajectories" from mathematics education that can paint the evolution of students' knowledge and skills over time over a set of learning experiences (Clements & Sarama, 2004; Simon, 1995; Sztajn et al., 2012; Corcoran, Mosher & Rogat, 2009; Maloney and Confrey, 2010). Curricula for undergraduate engineering programs can reflect an intended pathway of knowledge construction within a discipline. We intend our study of individual students within undergraduate engineering programs can highlight how this may happen in situ and how it may compare to a given, prescribed programs of study.

We use a theoretical framework based in adaptive expertise and design thinking adaptive expertise to develop a design learning continuum further (Hatano and Inagaki, 1986; Schwartz, Bransford, & Sears, 2005; McKenna, 2007; Neeley, 2007). The main research question is explored by collecting data through semi-structured interviews from both undergraduate engineering students and faculty members. We also conduct similar interviews with faculty who are responsible and knowledgeable for undergraduate programs about their perceived benefits for the structure of their program's curriculum. The data was then analyzed by using thematic content analysis. This research project also aims to deepen the understanding of how design activity, including making, can act as learning and reflection during the engineering design process (Adams et. al., 2003; Adams, 2001; Lande and Leifer 2009; Lande and Liu 2019). With an appreciation that the engineering design process serves as a teaching aid and as some measure of one's design learning, the concepts of design process geometries (Lande & Yiu 2019) and design learning trajectories can help develop the knowledge that is otherwise embedded in prototyping and artifact creation. In addition, such reflections on the engineering design process may help improve the teaching, learning, and practicing of engineering design. The findings from this work can benefit the larger engineering education research and design education communities by providing more effective frameworks for engineering design learning.

Methods

In order to better understand the research question how knowledge is constructed, ordered and developed over time for undergraduate engineering students, this study is composed of two parts and there were two types for the data the researchers collected and analyzed. The first type of data was individual students' and faculty reflections of their engineering learning trajectories navigating the curriculum. Faculty provided their perspectives towards students' expected learning trajectories. The second part used individual student drawings of their engineering design process. The first part used semi-structured interviews and thematic content analysis (Saldaña 2015, Patton 2002) to gain insights into the perceptions of how knowledge is constructed and ordered for engineering students from first to senior year, along a novice to expert spectrum. The second part used design process maps over time to obtain students actual engineering process data.

Student and Faculty Participant Interviews. For the first part of this study, four participants were recruited through snowball sampling. Among the four participants, one is a white, male freshman in software engineering, one is a Latina, female senior student in software engineering. Additionally, one white, male faculty member from software-engineering and one other white, male faculty member from electrical engineering were recruited. The rationale behind the recruitment is software engineering and electrical engineering are two of the typical engineering subjects that involve both hands-on building, teamwork, problem solving and other engineering-related skills. The two student participants represent both the dominant (white, male) and underrepresented (non-white, female) engineering student body. The two faculty participants have over two decades teaching experience at the college level for both traditional engineering students and non-traditional engineering students. Maximum variability draws out the greatest variety from the smallest number of participants in the hopes of providing the richest snapshot of the phenomenon.

Interview Protocols. The participants were asked to answer a few questions about their classroom experience and the learning goal/outcome. There were two versions of interview questions, faculty version and student version, trying to explore the same topics. The interview questions only varied slightly, asking both the faculty and the student to reflect on the expected student experience. Each interview lasted approximately fifty minutes. And an emerging thematic analysis will inform other prongs of the research. Example interview questions are listed below in Tables 1 and 2.

Table 1: Example interview questions in *Area 1: Classroom Experience*

Q:	Can you tell me your perceptions about students' expected learning experiences through the curriculum? Walk me through the classes students take? *(faculty)* *(probe)* What knowledge and skills are they expected to learn in these classes? *(probe)* Can you tell me about other things they are expected to learn?
Q:	How did you learn stuff relevant for your major through the curriculum? Can you walk me through the types of classes you have taken? *(students)* *(probe)* What knowledge and skills have you learned in these classes? *(probe)* Tell me about other things you have learned. *(probe)* Can you reflect on your courses?

Table 2: Example interview questions in *Area 2: Learning Goal/Outcome*

Q:	Can you tell me how do you think knowledge is structured /created /formed in your program? *(faculty/students)* *(probe)* We are interested in balancing between breadth and depth, how do you think breadth and depth can be applied in the specific content knowledge and context?
Q:	How does your program balance between theoretical class and applied class, which do you think students like better and why? *(faculty)*
Q:	How does your major balance between theoretical class and applied class, which do you prefer and why? *(students)*

All interviews were audio recorded, transcribed, and analyzed through thematic content analysis. The researchers used a memoing (Birks, Chapman & Francis 2008) method for the initial qualitative data analysis. At the second phase, the researchers engaged in pattern coding to reduce data. The goal was to triangulate what students thought they were learning, what they were being taught, and what their learning outcomes were in comparison with the perspectives from faculty as well. In addition, how these insights could be used to improve the current engineering education pedagogy was also of interest. Then, at the data synthesis stage, codes were organized around the research questions and the connections between themes in the data were discussed by the researchers.

Design Process Maps. For the second part, the researchers collected data from two undergraduate engineering courses over the course of one semester: a first-year introduction to engineering design course (45 process maps) and a sophomore-level introduction to human-centered design course (46 process maps). The common learning goal for both of these two courses was to apply a user-inspired design process and design tools to identify engineering needs, produce a documented design solution, demonstrate ability to collect, analyze and interpret data, through a project-based learning course structure. The researchers adopted the visual analysis methods in semiotics and iconography to classify students' engineering design process map visually, aiming to quantify the qualitative data (Leeuwen & Jewitt 2001). Through methods to analyze concept maps as tools for scientific learning, the researchers identified topics as "nodes," with directionality connecting through "links" and patterns more generally connecting within. The former might be readily identified as design process steps, the latter as indications for iteration. The researchers also explored the patterns and procedures of the engineering design and learning process, and graded the patterns as generally being linear, circular, successive, and adaptive. This was reflected through cognitive knowledge types and design expertise, specifically by identifying when and how declarative, procedural, and strategic knowledge was used. The second part of this study examined a collection of undergraduate engineering students' drawings of their design process. The researchers used a qualitative approach to code students' sketches of their engineering design process to extract a generalizable model for design learning. The researchers conducted analysis of these drawings as concept maps and documented the information at the start and end of a number of courses.

Findings

To better understand the research question "how knowledge is constructed, ordered and developed to adaptive expertise for undergraduate engineering students from freshman to senior year, along a novice to expert spectrum", the following general themes have emerged from the interview data analysis as well as from both the curricular maps and design process maps.

Top-Down Versus Bottom-Up. Professors reflected the whole learning pathway from a top-down approach while students used a bottom-up approach. In addition, professors have a better balance between breadth and depth.

Holistic Presentation of the Entire Curriculum. The researchers did a cross-case comparison for the software engineering freshman, senior and faculty. Some initial inclinations were found during the data analysis. Faculty tended to have the most holistic view and were able to make most connections between different courses. The senior student held a more holistic view but less long-term and made a fair amount of connections between various courses. However, she struggled with the balance between breadth and depth, and tried to figure out which career path she wanted to take in the future. The freshman had the least holistic view: lacked the connections between different courses and lacked the balance between breadth and depth.

Career-Mindedness. What the students had in common was that they both wanted to take courses that might be helpful for their future careers. However, before they figured out what they wanted to do in the future, they were still confused on how the courses fit together and how that could help in their future. They would be more motivated if they knew that a course was going to be helpful. Both the senior and the freshman student seemed to lack the bridge between academia and industry. The faculty also mentioned they were adjusting the curricula according to the industry's requirements.

Cognitive Apprenticeship. Once a tacit process is made visible, the research team can recognize that with the design process there is a common canon that serves as a basis for novices to learn engineering design. The steps in the design process serve as cognitive knowledge for the students to accumulate. At first, it is declarative knowledge, i.e., brainstorming is the generation of ideas. Then it can be procedural knowledge, for example, how one may use Post-It notes and employ a set of guidelines for how to brainstorm. It can then culminate in the strategic use of the design process to mindfully navigate design process steps in an economic, planned, and purposeful manner more akin to an expert. The affordances of the design process as a learning guide through this cognitive development can be mapped to a spectrum of varying types and representations of individual students' design process understandings. Through repeated practice in courses across curricula, one can discern the evolution of one's application of knowledge and skills in this cognitive apprenticeship mode. It makes sense then, with design challenges of increasing ambiguity within individual courses and topics, that one's design practice runs parallel to increasingly involved "zones of proximal development." This learning science perspective for design learning may serve to underscore and rationalize many of the unique pedagogical approaches one sees in a design course.

From the design process maps collected, the research team found that in the second-year course, students generally had more loops and revisits to previous steps in their engineering design process while in the first-year course, students usually followed a one-way direction step-by-step fashion in their engineering design process. It seems that in the second-year course, students had more complex mental models and were able to make more connections and reflections during their engineering design process and those in the first-year course.

In summary, the two types of data collected altogether demonstrate that students with more expertise are able to make their learning and design process more adaptive and reflective. They also tend to have a more holistic view of the whole learning/design process. Furthermore, they are more flexible to choose the appropriate strategy to make progressions during their learning/design process. It seems that the key thing is about making connections and being adaptive. Both of the interview data and the drawing tasks data reflected the participants mental models for how their courses fit together and how they conceive of the design process itself.

Discussion and Implications

Engineering design education is rooted in a design process as a means to learn, practice, and deploy technical knowledge to solve increasingly complex problems. Engineering students demonstrate their design prowess and design learning in the classroom, and across chains of classes, through either the creation of an artifact, or documentation and reflection on their engineering design process, or some combination of these. As design educators search for a means to understand design learning and evaluate what design learning should ideally look like, students' real and imagined understanding of their education, both through their appreciation of the map of courses towards their majors, and of the engineering design process being learning itself, has value. The engineering design process, and its explicit manifestation through student expressed concept maps can serve as both a model for learning and a means to capture a spectrum of design expertise. Reflections on the design process and, at a more holistic level, educational programs curricula, can help illustrate students' perspective on their learning and their developing expertise.

One of the goals of engineering education is to prepare engineering students to solve complex problems across disciplinary boundaries. Students may lack authentic, professional preparation in their coursework. Engineering students are situated in a slightly different environment from the industry, where their learning opportunities mainly come from class assignments and course work. There is a challenge for the formal engineering education system to produce sufficient numbers of qualified engineers to solve complex problems (Perry et al. 2008, Chen, Johri & Rangwala 2018, Cohen et al. 2006, Spencer, Steele & Quinn 1999, Steele 1997).

Being more transparent and explicit about how learning goals connect across courses can be helpful. The pedagogical approach within engineering courses can be more clearly communicated to students, and in particular the hands-on nature often found in engineering education. As a profession, and the practice of such, project-based learning has a specific benefit in engineering, as in other professional models of education for the law, medicine, and clergy (Sheppard et al 2009).

Through applying the concept of cognitive apprenticeship to a design learning experience, and ascribing the constructivist approach of the student demonstrating skill to the process itself, rather than to a person, we reconceive the role of the learner, teacher, and the engineering design process as a learning guide itself. We characterize aspects of one's representative design process concept map as a mental model and work towards means to describe what that snapshot can illustrate about one's design learning. There are opportunities to design new "process aware" engineering learning experiences. And the engineering curricula and the engineering design process can both serve as learning guides themselves.

Conclusions and Future Work

This study is exploratory in nature. To answer the research question about the process of undergraduate engineering students' knowledge construction and adaptive expertise development, the researchers explored how novices' and experts' mental models of an engineering learning process come into being and evolve through undergraduate engineering students' educational experiences.

Both of the learning process data and the design process data provides a guideline for educators to design the better "process aware" engineering learning experiences. It can also serve as a learning guide for the students to better navigate from the coursework and better reflect their own learning experiences. The next steps will be collecting more data to further extend the conclusions of this study and extend it to broader population in various learning and teaching settings.

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References

R. Adams, *Cognitive Process in Iterative Design Behavior.* Dissertation (Ph. D.) University of Washington. 2001.

R. Adams, J. Turns and C.J. Atman, What could design learning look like?, *Proceedings of the Annual Design Thinking Research Symposium VI*, November, Sydney, 2003

M. Birks, Y. Chapman and K. Francis, Memoing in qualitative research: Probing data and processes. *Journal of Research in Nursing*, 13(1), 68-75, 2008.

Y. Chen, A. Johri, H. Rangwala. Running out of stem: a comparative study across stem majors of college students at-risk of dropping out early. *Proceedings of the 8th International Conference on Learning Analytics and Knowledge,* 2018 Mar 7 (pp. 270-279). ACM.

D.H. Clements and J. Sarama, Learning trajectories in mathematics education. *Mathematical thinking and learning*, 6(2), 81-89. 2004.

G.L. Cohen, J. Garcia, N. Apfel, A. Master. Reducing the racial achievement gap: A social-psychological intervention. *Science*. 2006 Sep 1;313(5791):1307-10.

J. Confrey and A. Maloney, The construction, refinement, and early validation of the equipartitioning learning trajectory. In *Proceedings of the 9th International Conference of the Learning Sciences-Volume 1* (pp. 968-975). International Society of the Learning Sciences, June 2010.

T.B. Corcoran, F.A. Mosher and A. Rogat, A. (2009). Learning progressions in science: An evidence-based approach to reform, *CPRE Research Report# RR-63*. New York: Consortium for Policy Research; 2009 May.

G. Hatano and K. Inagaki, Two courses of expertise. In H. Stevenson, H. Azuma, & K. Hakuta (Eds). *Child development and education in Japan* (pp. 262-272), NY: Freeman, 1986.

M. Lande and L.J. Leifer, Work in progress-student representations and conceptions of design and engineering. In *2009 39th IEEE Frontiers in Education Conference*, pp. 1-2. IEEE, 2009.

M. Lande and Y. Liu, Design Process Geometries: Shapes and Learning Trajectories of Engineering Students' Design Process Concept Maps, Proceedings of ASEE Annual Conference, Tampa, FL, 2019.

A.F. McKenna, An investigation of adaptive expertise and transfer of design process knowledge. *Journal of Mechanical Design*, 129(7), 730-734, 2007.

W.L. Neeley, *Adaptive design expertise: A theory of design thinking and innovation* (Doctoral dissertation, Stanford University), 2007.

M.Q. Patton, *Qualitative Research and Evaluation Methods*, Thousand Oaks, CA, Sage Publications, 2002.

W. Perry, A. Broers, F. El-Baz, W. Harris, B. Healy, W.D. Hillis, et al. *Grand challenges for engineering*. National Academy of Engineering, Washington, DC, 2008.

J. Saldaña, *The Coding Manual for Qualitative Researchers*, Thousand Oaks, CA, Sage Publications, 2015.

D.L. Schwartz, J.D. Bransford and D. Sears, D, Efficiency and innovation in transfer. In J. Mestre (Ed.), *Transfer of learning: Research and perspectives* (pp. 1–51). Greenwich, CT, Information Age, 2005.

S.D. Sheppard, K. Macatangay, A. Colby, W.M. Sullivan, *Educating Engineers: Designing for the Future of the Field*, San Francisco, CA, Jossey-Bass, 2009.

M.A. Simon, Reconstructing mathematics pedagogy from a constructivist perspective. *Journal for Research in Mathematics Education*, 26, 114–145, 1995.

S.J. Spencer, C.M. Steele, D.M. Quinn. Stereotype threat and women's math performance. *Journal of experimental social psychology*. 1999 Jan 1;35(1):4-28.

C.M. Steele. A threat in the air: How stereotypes shape intellectual identity and performance. *American psychologist*. 1997 Jun;52(6):613.

P. Sztajn, J. Confrey, P.H. Wilson and C. Edgington, Learning trajectory based instruction: Toward a theory of teaching. *Educational Researcher*, *41*(5), 147-156, 2012.

T. Van Leeuwen and C. Jewitt, eds. *The Handbook of Visual Analysis*. Sage, 2001.