WIP: Changes in Students' Understanding and Use of Representations During a Design Course

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Abstract— **This work in progress (WIP) research paper describes student use of representations in engineering design. While iterative design is not unique to engineering, it is one of the most common methods that engineers use to address socio-technical problems. The use of representations is common across design methodologies. Representations are used in design to serve as external manifestations of internal thought processes that make abstract concepts tangible, enhance communication by providing a common language, enable iteration by serving as a low-effort way to explore ideas, encourage more empathetic design by capturing users' perspectives, visualize the problem space, and promote divergent thinking by providing different ways to visualize ideas. While representations are a key aspect of design, the effective use of representations is a learned process which is affected by other factors in students' education. This study sought to understand how students' perceptions of the role of representations in design changed over the course of a one-semester design course. Small student teams created representations in a three-stage process—problem exploration, convergence to possible solutions, and prototype generation—that captured their evolving understanding of a socio-technical issue and response to it.**

The authors hypothesize that using effective representations can help develop skills in convergence in undergraduate students; one of engineering's contributions to convergent problem solving is design. More specifically, this research looked at students' use of design representations to develop convergent understanding of ill-defined socio-technical problems. The research questions focus on how students use representations to structure sociotechnical design problems and how argumentation of their chosen solution path changed over time. To answer these questions this study analyzed student artifacts in a third-year design course supported by insights on the process of representation formation obtained from student journals on the design process and a self-reflective electronic portfolio of student work. Based on their prior experiences in engineering science classes, students initially viewed design representations as time-bound (e.g. homework) problems rather than as persistent tools used to build understanding. Over time their use of representations shifted to better capture and share understanding of the larger context in which projects were embedded. The representations themselves became valued reflections on their own level of understanding of complex problems, serving as a self-reflective surface for the status of the larger design problem.

Keywords—Design process, Mental models, Student development, Metacognition

I. Introduction and Review

This WIP research study explores how undergraduate students develop and express skills that we hypothesize are important in addressing convergent problems [1], [2], [3] [4]. 'Convergence' is a term that captures the need for individuals from multiple disciplinary backgrounds to work together to address pressing societal, technical, and scientific challenges. Convergence is a 'catch-all' term with a definition that varies by context depending on the goals and the processes by which it is assumed to occur. The goals of convergence [4] generally include elements of addressing socially relevant problems, translating research into the commercial realm (e.g. Pasteur's quadrant [5]), fundamental knowledge discovery, local and context-specific application, and increasing research productivity. The process through which individuals develop the skills to achieve these goals include focusing on societal issues, integrating work across disciplinary boundaries, using established methods of forming effective teams (team science [6]); working on a diverse team that engages multiple disciplines, and incorporating elements of entrepreneurship. Convergence is not engineering-specific, rather engineers work with those from other disciplines to address convergent problems.

Problem solving is central to the identity of engineering faculty [7]. Homework assignments and exams are used to practice simple problems and projects provide more complicated problems. As students advance through the program the difficulty of problems typically increases, reflecting growing knowledge and skills. While much work in convergence has focused on graduate students and established researchers [2], [3] at the current time there is not yet a clear picture on how individuals' undergraduate education helps them become interested in and steer their careers towards addressing convergent problems or preparation the results in the skills needed to do so.

Problems, particularly convergent problems, are more multidimensional than a one-dimensional classification from simple to complicated implies. Jonassen—looking at problem solving in the design space—captured this dimensionality by creating a typology of problems [8]. While many engineering classes assume that achieving designated learning outcomes teaches students generalizable knowledge and skills that can be applied across different learning domains, Jonassen points out that in actuality problems are domain-specific and depend on context. In other words, achieving different learning outcomes requires supporting different learning methods and environments. This is especially true for problems that cross domains, are ill-structured, and complex; in other words the types of problems students encounter in engineering design rather than engineering science classes. These are also hallmarks of convergent problems.

Problem solving is a multidimensional space with at least three overlapping aspects: the problem type, the problem representation, and the characteristics of the individual solving the problem [8]. The type of problem being solved can be described on overlapping dimensions of abstraction, structure, and complexity. Abstractedness varies from highly abstracted to highly situated. A key skill in engineering that distinguishes it from science is being able to move both ways on a vector from abstract to situated [9], [10]. Problems can also be well- or ill-structured. Well-structured problems limit the size of the 'problem space' by providing needed information, having defined rules, and clear paths to solutions. Less structured problems require the problem solver to provide structure, often by synthesizing across domains and integrating disparate skills. Cognitively complex, as opposed to simple, problems are defined by a problem space with a large number of dimensions, requiring more cognitive operations which make the problem more difficult to solve.

How problems are represented also determines the way problems are solved. Problems encountered in everyday life or work are embedded within specific, individual contexts while problems in academic settings are typically abstracted to show generalizability. Such highly abstracted problems often use mathematical or symbolic representations that may be specific to a discipline. Designers also use formal and informal representations to gain insights into different aspects of the problem space during the solution process [11], [12], [13]. Moving from being a novice to being an expert in the design space includes becoming facile with problem representation. During design activities problem solving also shifts between divergent and convergent modes of thinking, which each require different sets of skills and thus different representations [14]. Because they help support learner schemas, representations have been used in various disciplines, including engineering [15], [16] and math to improve understanding and problem solving.

II. Background and Context

The study reported here was undertaken in a required half-credit (2 credit hour) course for third-year students in an electrical and computer engineering program. The course is the fourth design course in a six-course sequence, focusing particularly on problem identification and the early phases of design. In prior courses students have learned design frameworks and undergone a highly scaffolded design project to produce an internet of things sensing and display node. In the course in which this study is conducted, students independently choose one of the United Nations Sustainable Development Goals [17], research the multiple and interlocking issues related to the goal, and then identify different aspects of the goal that are amenable to technological interventions. After ranking their interest in possible solution paths, student teams are formed by the instructors and then are given complete freedom to come up with a solution; instructor input on possible project directions is supportive rather than directive.

The design course is divided into three consecutive phases of five weeks each: 1) research and problem identification, 2) project planning, and 3) creating a minimum viable product (MVP). In each phase teams learn a variety of design representations in a flipped-classroom format [18], explaining their design choices using representations at the end of each phase at a demonstration and through a formal report. Feedback by the course instructors is offered formatively during class and summatively at the end-of-phase design check-ins. There are no exams. This course structure is intended to align with many of the goals and processes of convergence, outlined previously, particularly emphasizing contexts outside engineering and social aspects of problems, utilizing an entrepreneurial approach including mandatory interviews of experts, and supporting radical collaboration between teams.

Student teams (3-4 individuals) create multiple written and physical representations. These include causal system maps in the problem identification phase [19], entrepreneurial problem framings [20], engineering representations like block and flow diagrams [21], and the MVP prototype. In this work in progress we focus primarily on two of these representations, the block diagram and system map since these capture the divergent and convergent phases of design.

III. Initial Study Design

Design representations are formalized mental models or schemas that help to promote shared understanding within a community, in this case between engineering students and faculty in the design class. Having valid schemas that enable manipulation of the problem space is necessary to solve complex problems [8], [22]. To explore how students' development and use of design representations impacts on their interest and ability to address convergent problems at the undergraduate level, this study analyzed student artifacts and self-reflections over the duration of the one-semester course. The preliminary analysis in this WIP paper is guided by two research questions:

- RQ1 – How do students utilize design representations to engage with socio-technical, convergent design problems?
- RQ2 – How do students describe changes that occur in their cognitive, affective, and conative abilities in using design representations to address a convergent problem?

The data set is drawn from three different sources collected from the Fall 2023 and Spring 2024 semesters; only Spring 2024 is reported in this work-in-progress paper. The student artifacts include weekly reflections, an end-of-semester e-portfolio, and team reports. Reports were written in three phases corresponding to each phase of the course with in-depth feedback on writing elements and structure provided through an instructor-scored rubric. Additional insights on student use of representations were discussed in student reflections on the design course collected through weekly reflections on the Basecamp platform [23]; instructors responded to each reflection. An end-of-semester electronic portfolio utilized a Hero's Journey [24] template to elicit student experiences. These artifacts were uploaded as text to NVivo with the aid of the AI tool ChatGPT 4 to strip out irrelevant text (e.g. instructor responses or instructions) and HTML coding. For this WIP paper we drew primarily from weekly reflections since they provided rich insights and enabled analysis of students' interaction with design representations over time.

The overall sample consisted of 29 students taking the third-year design course with 14 students in the fall cohort and 15 in the spring. One limitation is demographic skew – students were ~62% white, male, US citizens; ~21% were women; and ~20% non-white, of which half were international students. One potential confound is minor changes to class schedule and content between the two semesters, however the artifacts analyzed did not change over the two semesters. For this work-in-progress paper we focused on four individuals: Madeline, an academically engaged Asian American female student; Fred, a white male student heavily engaged in Greek life but less engaged academically; Peter, an outspoken white male student who is strongly technically focused; and Gus, a quiet and introverted white male student. These four students were chosen because each represented observed sub-sets of students in the class. The student names used are pseudonyms.

Preliminary coding of artifacts was done by two of the authors using elements drawn from Jonassen's typology [8], characteristics of convergence [4], as well as open coding. Part of the WIP work presented here is to develop and validate the coding scheme; future work will involve coding the larger dataset. From Jonassen's typology the three elements of problem solving—problem variations, form of representation, and individual differences—were coded with subtypes as were the types of problems [8]. Convergence codes focused on outcomes and process, with additional sub-codes for elements of team science [4]. Open codes were added in support of convergence, problem solving, or representations in areas codes drawn from the cited literature were not complete.

IV. Results and Discussion

While multiple design representations were used in the design process, this WIP paper focuses on system maps to explain complex socio-technical contexts and block diagrams that highlight how engineered solutions are architected using methods of functional decomposition. For the first research question, how engineering students utilize design representations to engage with problems, initially students treated creating representations like homework assignments; that is they saw representations as a transient part of the class. However, as students continued to engage with and refine the same representations over the course of the semester, they begin to see the way representations informed their thinking. For example, Peter said "*...our team was working on our system map of the water problems outlined by the UNSDG* [United Nations Sustainable Development Goal]. *I found the experience to be quite interesting as I always felt like there was another variable we could consider. Or yet another cause and effect.*" A similar comment by Gus highlighted the role of representations in understanding larger problem contexts "*We were missing the bigger picture. To get around this issue I suggested that for the second iteration of our system map that we start with a basic loop of how humans take water, consume it, and then re-enters the water supply and then from there we would be able to add loops to this to about how people are affected.*" Similar comments were made by all four students as their understanding of the problem increased and their view of the role representation played in design changed.

The system maps created by student teams were surprisingly comprehensive, with an average of 18 nodes, 27 edges, and 4 different archetypes [19] identified. In coding student comments about creating and using system maps it was found that very few of the simpler forms of problems were discussed; the most common problem was Jonassen's strategic performance which "involves real-time, complex and integrated activity structures, where the performers use a number of tactics to meet a more complex and ill-structured strategy while maintaining situational awareness" [8]. An example is Fred reflecting that "*One of my biggest takeaways from this week came from classifying the different archetypes that the loops of a system can be classified by. Through classifying archetypes one can learn to view a system as a whole and devise possible solutions that solve the issue systemically rather than mediating* [sic]*it until the next iteration of the loop. This was an exciting thing to learn about because solving complex problems like this will more than likely become a big part of my life once I enter the professional world.*" Other problem typologies that occurred frequently included involved decision-making problems—selecting the most satisfactory option from several choices—and diagnosis-solution problems that address making strategic decisions.

Block diagrams as well as system maps hinted at a form of problem not mentioned in Jonassen's typology that we categorized as 'Research Framing Problems'. This code corresponded to points in student reflections that discussed performing and synthesizing research and/or integrating knowledge from different sources into their project. Students frequently commented on needing to refine their knowledge or determining how to represent it appropriately. For example, Gus reflected on a decision to build the team's knowledge before defining some aspects of their project: "*Ultimately we decide that for now it was best to keep researching the topic to build our base of knowledge so we could get more creative ideas on the issue later on, which I am glad with. I think if we tried to lock ourselves into a certain path already it wouldn't be helpful.*" Similarly, Madeline observed "*Since we are starting to plan the details of our project, which deals with measuring water quality at a water treatment facility, we asked many technical questions about the process of testing the water. We learned a lot of information on current water treatment testing procedures, which we can apply to how we execute and evaluate the performance of our own water quality and alert system.*" Independent research—both through reading literature and performing interviews—was emphasized in the structure of the course; the number of references to research throughout the reflections indicated this was important to overall success of student teams.

The second research question focuses on understanding the changes in student cognitive, affective, and conative abilities they report through using design representations. As has been observed by other authors, design teams develop their own terminologies as the take ownership of problems [12], a process Peter observed was aided by representations: "*I do think it's interesting that engineers use block diagrams to most easily communicate their designs. Because as I've gone through school I've noticed that a lot of the engineers around me, myself included, start talking in almost incomprehensible terms if you don't already know the engineering topic. As well as learning many different technical topics it's almost liked we learned a new language.*" This theme of representations connecting ideas was echoed by other students as they continued to revisit their work: "*I noticed however that as we were trying to create our level 1 block diagram that we ran into some problems. We need to understand the different parts we intend to use and how the connections between them will work. We hadn't thought about how some subsystems would be interacting and which led to some confusion and we realized we need to do some more research"* [Gus].

Over time students begin to see representations as shared forms of knowledge that were useful to (imperfectly) capture the complexity of working in a socio-technical system. For example, Gus compared representations to understanding gained in another class "T*his process also reminded me of something that we have been discussing in my physics course. We have been talking about models and how and why we create models. We have talked about how models are used to help us understand a real world process or phenomenon that is hard to explain and can put it in a way that is easier to understand. This is exactly what creating the system map is doing for me, helping me understand a complex real world problem.*" Representations also began to be used as a tool for questioning and decision-making. For example, Madeline noted that "*This process* [creating a block diagram] *challenged us to be clear on the inputs and outputs of our system, and to be specific about how the inputs and outputs interact with the system, by thinking about the means in which these interactions and actions would occur*."

In the second month of the class Madeline highlighted the growing understanding that representations were generalizable tools used in the design process: "*Having a tool that allows for visual learning will help me understand these cause and effect connections between entities in a system, so I look forward to further developing our system map throughout the project.*" This was echoed by Fred who saw representations as a way to clarify disconnects in the team's understanding of the system they were building "*...I realized the further information and refinement that our design requires. Explaining the functionality of a design through words is pretty easy but the missing pieces and incongruence of a design really shine* [sic] *when it is put on paper.*" Revisiting representations appeared to help students connect various aspects of the design process.

There is some evidence that creating representations aligns with elements of convergence, particularly those of team science [6]. Students found the unstructured projects encouraged goal setting and alignment, working collaboratively, communication, and evaluating and adapting to changing circumstances. Fred, struggling with expectations for the completeness of the system map, recognized that external experts can help refine goals: "*In light of this, it is important to constantly research and develop our system map. From this, we can most reliably arrive at a practical solution. Given this goal, it is important to interview experts who have already researched these topics to confirm/deny our assumptions.*" Gus agreed that external expertise had great value: "*...the interviews have been some of the most important and guiding parts of the project so far that I cannot say was true in other classes. I am very glad this interview process is a part of this class as I feel it is an extremely valuable skill to have and I am even drawing connections between this and being in the interview process for internships.*" There were a substantial number of comments on the importance of forming functional teams as illustrated by Peter's comment that "*After meeting with my team on Wednesday, we wrote out a list of norms that everyone should follow. I think the most important of these was good communication, as that can often lead to one or more members either not pulling their weight or feeling left out.*"

While few students discussed outcomes of convergence, the processes used in convergent problem solving were mentioned more frequency. Socially relevant problems were often cited, with codes for social relevance correlating with codes for motivation. Similarly, students connected their work on developing MVPs later in the course to commercialization and entrepreneurship. Madeline commented that having design problems embedded in social contexts made them connect more to user needs: "*The more I wrote, the more I began to see how our research connected and informed different parts of our design. For instance, our interviews in phase 2 helped us think more about the social aspect of things by providing water quality data to the public, which we originally did not think about in our water quality monitoring system. This allowed us to be more understanding of the users of our product.*"

It is important not to over-interpret these preliminary findings as support for the development of convergent thinking in this cohort of students. Determining that student efforts align with published outputs and processes of convergence is not evidence they are developing skills to work on convergent problems or can transfer what they learned to later endeavors. More work is needed to expand the sample, revise the codes, and determine the role representations play as students build their understanding of addressing convergent problems. Additionally while these initial results tentatively confirm students utilize the types of skills needed to address convergent problems, much remains unknown about the overall development of researchers who can effectively address these types of problems [1].

V. Conclusion

This WIP paper shares preliminary results showing some of the ways that design representations help undergraduate students develop habits and schemas to address complex, contextualized, and cross-domain problems that are hallmarks of convergence. While the authors are still developing and validating codes based on the small set of artifacts analyzed to-date, coding to Jonassen's typology indicates representations are able to focus students on more complex problems situated in existing social and technical contexts.

To better capture the ways representations impacted student learning, a new aspect of problem-solving—'research framing'—is hypothesized that captures the role diagraming and building shared understanding across a team occurs. Research framing occurred across the course and across different representations once students shifted their view of representations to a tool useful in design rather than as a single occurrence 'homework-type' assignment.

Overall, the focus of the design course on representations rather than creation of a prototype project does seem to cause students to better understand how problem context, including societal and cultural aspects, impacts upon technical solutions. Prior research has shown that engineering students' focus on the technical aspects of problems results in declining interest in the larger contexts and implications of engineering [25]. This is well-captured in technically-focused Peter's summative reflection in the end-of-semester electronic portfolio: "*I think this course really emphasized a granular level of thought for every step in the process. This was something that was quite new to me. Before this, I saw the engineer as someone who simply takes in problems, creates a solution and spits it out. But there is so much more to the process. An engineer might have to consider far more factors that go well beyond their current knowledge. They might even have to reconsider the problem as a whole. Whether the identified problem is really the cause or perhaps a solution to this problem is only fixing a minor symptom of something far greater.*"

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REFERENCES

[1] B. Akbar, J. L. Brummet, S. C. Flores, A. Gordon, B. Gray, and J. S. Murday, "Global Perspectives in Convergence Education," National Science Foundation, Organization for Economiic Cooperation and Development, National Academies, Department of State, University of Southern California, Washington D.C., 2017. [Online]. Available: https://www.nsf.gov/nano/ConvergenceEducation

[2] Committee on Key Challenge Areas for Convergence and Health, *Convergence: Facilitating Transdisciplinary Integration of Life Science, Physical Sciences, Engineering, and Beyond*. Washington D.C.: National Academcy Press, 2014. doi: https://doi.org/10.17226/18722.

[3] M. C. Roco, W. S. Bainbridge, B. Tonn, and G. Whitesides, Eds., *Convergence of Knowledge, Technology and Society: Beyond Convergence of Nano-Bio-Info-Cognitive Technologies*. in Science Policy Reports. Cham: Springer International Publishing, 2013. doi: 10.1007/978-3-319-02204-8.

[4] M. S. Thompson *et al.*, "What is Convergence?: A Systematic Review of the Definition of and Aspects of Convergent Work," in *2023 IEEE Frontiers in Education Conference (FIE)*, College Station, TX, USA: IEEE, Oct. 2023, pp. 1–5. doi: 10.1109/FIE58773.2023.10343511.

[5] D. E. Stokes, *Pasteur's Quadrant, Basic Science and Technological Innovation*. Washington DC: Brookings Institute Press, 1997.

[6] K. L. Hall *et al.*, "The science of team science: A review of the empirical evidence and research gaps on collaboration in science.," *Am. Psychol.*, vol. 73, no. 4, pp. 532–548, May 2018, doi: 10.1037/amp0000319.

[7] A. L. Pawley, "Universalized Narratives: Patterns in How Faculty Members Define 'Engineering,'" *J Eng Educ*, vol. 98, pp. 309–319, 2009.

[8] D. H. Jonassen, "Toward a design theory of problem solving," *Educ. Technol. Res. Dev.*, vol. 48, no. 4, pp. 63–85, Dec. 2000, doi: 10.1007/BF02300500.

[9] J. Krupczak and G. Bassett, "Work in progress: Abstraction as a vector: Distinguishing engineering and science," in *Proceedings - Frontiers in Education Conference, FIE*, 2012. doi: 10.1109/FIE.2012.6462373.

[10] S. L. Goldman, "Why we need a philosophy of engineering: a work in progress," *Interdiscip. Sci. Rev.*, vol. 29, pp. 163–176, 2004.

[11] N. Cross, "Expertise in Design: An Overview," *Des. Stud.*, vol. 25, pp. 427–441, 2004.

[12] L. Bucciarelli, *Designing Engineers*. Cambridge, MA: The MIT Press, 1996.

[13] M. S. Barner, S. Adam Brown, F. Bornasal, and D. Linton, "Tangibility of representations in engineering courses and the workplace," *J. Eng. Educ.*, vol. 111, no. 1, pp. 162–184, Jan. 2022, doi: 10.1002/jee.20439.

[14] C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey, and L. J. Leifer, "Engineering Design Thinking, Teaching, and Learning," *J Eng. Educ.*, vol. 94, p. 103, 2005.

[15] T. J. Moore, R. L. Miller, R. A. Lesh, M. S. Stohlmann, and Y. R. Kim, "Modeling in engineering: the role of represntational fluency in students' conceptual understanding," *J. Eng. Educ.*, vol. 102, no. 1, pp. 141–178, 2013.

[16] B. Davidowitz and G. Chittleborough, *Multiple Representations in Chemical Education*, vol. 4. 2009. [Online]. Available: http://link.springer.com/10.1007/978-1-4020-8872-8%5Cnhttp://dx.doi.org/10.1007/978-1-4020-8872-8_9

[17] United Nations, "United Nations Sustainable Development Goals," United Nations. [Online]. Available: https://sdgs.un.org/goals

[18] C.-Y. Chao, Y.-T. Chen, and K.-Y. Chuang, "Exploring students' learning attitude and achievement in flipped learning supported computer aided design curriculum: A study in high school engineering education," *Comput. Appl. Eng. Educ.*, vol. 23, no. 4, pp. 514–526, 2015, doi: 10.1002/cae.21622.

[19] D. P. Stroh, *Systems Thinking For Social Change: A Practical Guide to Solving Complex Problems, Avoiding Unintended Consequences, and Achieving Lasting Results*. White River Junction, VT: Chelsea Green Publishing, 2015.

[20] C. R. Carlson and W. W. Wilmot, *Innovation: The Five Disciplines for Creating What Customers Want*. New York: Crown Business, 2006.

[21] R. M. Ford and C. S. Coulston, *Design for Electrical and Computer Engineers*. New York: McGraw-Hill, 2007.

[22] M. B. McVee, K. Dunsmore, and J. R. Gavelek, "Schema Theory Revisited," *Rev. Ed. Res.*, vol. 75, no. 4, pp. 531–566, 2005.

[23] "Project management software, online collaboration," Basecamp. Accessed: Apr. 24, 2023. [Online]. Available: https://basecamp.com/

[24] J. Campbell, *The Hero's Journey: Joseph Campbell on his life and work*. New York: Harper & Row, 1990.

[25] E. A. Cech, "Culture of Disengagement in Engineering Education?," *Sci. Technol. Hum. Values*, vol. 39, no. 1, pp. 42–72, 2014, doi: 10.1177/0162243913504305.