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SHORT PAPER: THINKING ABOUT DESIGN THINKING: TOWARD CAPTURING STUDENTS' METACOGNITION IN SOLVING DESIGN PROBLEMS

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ABSTRACT

In this short-paper we describe the ongoing development of a research methodology toward accessing how students think about design. Consideration of the formulation of a design problem statement that is suitable for supporting discussion with students from multiple disciplines at various points in their engineering education is the specific focus. The discussion draws from work on problem typology, design thinking, and metacognition as a theoretical basis that informs the problem formulation and planned approach for analysis.

INTRODUCTION

An important and recognized challenge for undergraduate engineering programs is the provision of experiences that yield growth in students' insight on what it means to be an engineer in practice. Many programs encourage and facilitate 'experiential learning', where activities that enable learning by doing and further reinforced through reflective activities are integrated into the curriculum [1]. A variety of experiential mechanisms are utilized in engineering education, including student clubs, internships, co-operative education, capstone designs, and others. Opportunities like these have been shown to be valuable in helping students transition from theory to practice [2–5]. However, for experiential learning to be meaningful and translate to the engineering profession, students must be capable of internalizing and effectively relating those experiences to well-developed professional competencies.

As part of ongoing research we are investigating the hypothesis that providing a problem typology and complementary reflection framework as context for student experiences will improve their ability to internalize and communicate the professional relevance of those experiences. This hypothesis is derived from work of David Jonassen to describe problem types and their importance to the design of educational environments [6,7], including engineering education environments [8,9].

Adopting Jonassen's work for framing educational experiences for undergraduate engineers, we propose that the problem typology framework can be instrumental in informing, assessing, and guiding student problem solving in experiential learning contexts. Using mixed methodology we are exploring students' problem solving abilities, epistemological stances, recognition of typology in and out of course and extracurricular project context, and students' ability to convey the essence of their experiential work in professional contexts. As part of the research we have particular interest in collecting data that reflects how engineering students think about different types of problems, including design problems, the core activity of engineering [2]. This has led to a fundamental question of interest that is explored in this work-in-progress paper:

How do we formulate design problem statements to evoke a metacognitive approach to design thinking?

Answering this question has implications beyond this research project. There is increased desire for "design thinkers" in engineering, and beyond [10] and a recognition that engineers must be accountable for outcomes that go beyond technical performance and include social, environmental, and ethical considerations [11].

ABET reflects these expectations in defining student outcomes that include an ability to design in a way that considers issues of economic, environment, social, political, ethical, and health provenance (outcome c). Further, the curricula is expected to provide a basis for understanding the impact of engineering solutions in global, economic, environmental and social context (outcome h) and knowledge of contemporary issues (outcome j). That is, the curricula must provide mechanisms by which students can participate in design activities that necessitate consideration of these broader issues.

In meeting these expectations and developing educational experiences that allow students to learn about and take part in design problem solving, it is critical to think about assessment.

This paper explores important issues related to assessment through the lens of problem typology and metacognition.

The remainder of this paper is broken up as follows. First, literature related to metacognition, problem typology, design education and assessment is briefly reviewed. Second, discussion of the research methodology is presented, covering both the development of the data collection instrument and anticipated approach to analysis. The paper concludes with a brief discussion about the future of this work and extension to other problem types.

BACKGROUND: METACOGNITION AND DESIGN

In addressing the question of design problem formulation and evoking metacognition among engineering students, the nature of problem characteristics, metacognition, and 'good' design are important considerations.

Problem Types and Characteristics

Jonassen describes 11 types of problems in developing a theory of problem solving [6]. Further, he argues that the foremost role of an engineer is that of "problem solver" with a specific focus on problems of design, selection, and troubleshooting [8,9]. Of particular relevance to this work are ideas regarding the ways in which problems differ [6] on two dimensions, variation and representation of problems.

Problems are said to vary in terms of their structured-ness (well- vs. ill-structured), complexity, and domain-specificity (abstract vs. situated). Well-structured problems are those that are found most commonly at the university level at the end of textbook chapters, with well-defined constraints and narrow context for relevant concepts, rules and principles. Ill-structured problems however, are more commonly encountered by engineers in professional practice and do not necessarily set constraints or imply a solution path. Instead, ill-structured questions require the integration of multiple content domains, and strategies to solve the problem [6].

Complexity considers characteristics like the number of issues, functions, or variables in a problem; connectivity of those characteristics; the dynamic nature of the problem, etc. [6]. Problem complexity is fundamental to defining and making tradeoffs that are common in design.

With regard to problem representation, context, problem cues or clues, and modality are important characteristics. Context is valuable in helping problem solvers determine which information is important and which is irrelevant.

Problem clues and modality (i.e. the way in which particular information is presented) are particularly important to the design of educational problems. Under the control of the instructional designer, these problem attributes significantly impact the difficulty of the problem.

We pay particular attention to problem framing in light of Jonssen's problem attributes [6]. These attributes include: (i) learning activity, (ii) inputs, (iii) success criteria, (iv) context, (v) structuredness, and (vi) abstractness. Our study considers these attributes as an important part of creating an engineering design question that will evoke detailed responses from students. It is through consideration of these attributes that we seek to refine the development of appropriate design problem statements.

Metacognition

Internalizing and communicating professionally relevant experiences is critical to being an effective engineer. In our study to "internalize and communicate experiences" refers to a student's metacognition of their design thinking and solving of engineering problems.

We look to metacognition as the self-monitoring of one's own cognitive processes and influences when they are focused on a specific task or goal [12, 13]. In addition, metacognition deals with the awareness of how one learns, the ability to judge the difficulty of a task, the monitoring of understanding, the use of information to achieve a goal, and assessment of the learning process [12].

Metacognition is a major influence in cognitive performance and in monitoring students' cognitive experience four areas of metacognition should be considered: metacognitive knowledge, metacognitive experiences, goals (tasks), and actions (or strategies) [12].

In our study we plan to analyze students' metacognition through problem discussions, reflections, and interviews through a form of discourse analysis. Most research recognizes two fundamental components of metacognition: cognitive knowledge and cognitive regulation [14, 15]. In our study, Jonassen's problem typology framework introduces knowledge about available strategies and when to use a particular strategy, thus it contributes to students' cognitive knowledge. Interventions and coaching sessions that demonstrate how to use problem typology in planning solutions, monitoring progress, and evaluating proposed solutions exemplify cognitive regulation [16].

The specifics of the framework for discourse analysis are still being developed and we expect to take a grounded theory approach while drawing from prior work in engineering education [17–19] and beyond [20–23].

Assessing Design and Design Thinking

Universally, accredited engineering programs provide students a capstone design experience. Many, programs offer first- and/or second- year "cornerstone" design experiences where focus is on early phases of design and concept development [2] and increasingly it is the case that students encounter design regularly, not just as "bookend" curricular experiences. Design thinking, made famous by IDEO, increasingly recognizes the value of putting users at the center of technology development [24] and is expected to drive many of the work environments that engineering students will join in the future. Involving students in purposeful educational interventions that facilitate design thinking is important to producing engineers with the breadth of interconnected competencies necessary for success in practice [25].

Regular and accurate assessment of students' learning about design is important. This means that a basis for assessment is vital as well, but finding a singular definition or central theory for "design thinking" is elusive [10]. A useful definition comes from a review of design thinking literature [26] that summarizes design thinking as an analytic and creative process that engages a person in opportunities to experiment, create and prototype models, gather feedback, and redesign. Representing design as a process, one that typically requires iteration, is useful to teaching and consistent with how design is presented in academia and industry.

It is also helpful to adopt the notion put forth by Dorst [10] where design is framed as abductive reasoning in which designers must simultaneously develop an artefact ("thing") and working principle (requirements, function, form, etc.) in order to create value for prospective users of that artefact. The challenge of simultaneously developing the 'thing' and 'working principle' requires designers to develop and adopt strategies for design ("design reasoning") is palpable. According to Dorst, experienced designers "tend to have much more deliberate [and efficient] strategies to tackle the complex creative challenge of coming up with both" [10].

Accessing students' "design reasoning" is important to assessing their professional preparation as engineers in addition to just measuring the quality of design education interventions. This reasoning might be expected to take form in: (i) iterative divergent-convergent thinking and inquiry, (ii) overall vision through systems thinking/design, (iii) managing uncertainty, (v) decision-making, (vi) team oriented social process, and (vii) communicating in "languages of design" [2]. In relating to design as studied among practitioners, characteristics may also include ideas about (i) evidence based decision-making, (ii) organized translation, (iii) personal synthesis, (iv) intentional progression, (v) directed creative exploration, and (vi) freedom [27].

There have been several design studies seeking to measure these types of design characteristics among students. Such studies include investigations into problem formulation [28, 29], concept design issues like creativity [30, 31], and concept selection [32]. Other studies have leveraged design documentation [33, 34], design notebooks and sketches [35, 36] and other reflective activities as a window into students' design thinking [17, 37]. Though these studies are not exhaustive it provides evidence of the types of activities and ideas design educators and researchers deem important and potentially valuable to assessing and differentiating 'effective' design practices.

A gap in understanding how students think about design that is of interest here is focused on how design problems are represented to students. As it relates to our ongoing research, we are investigating the development of design problem statements that are useful to short discussions with small groups of students. As we see these discussions as a potentially valuable way to access how students think about design, considering the construction of design problem statements is important.

METHOD – WORK-IN-PROGRESS

A unique element of our current research is to expose gaps in engineering students thinking while they are considering either an engineering design problem or an engineering case analysis problem. While both questions will be investigated in similar ways, for this work we focus on engineering design questions. In small groups, 2-4 students are given an ill-structured engineering design question.

Students are first given the opportunity to silently consider the question, then collaborate as a whole group to discuss ways to best solve the problem. After some group work and independent thinking, students are prompted by an interviewer in deeper thinking of the design question. It is during this short problem discussion that we seek to access the design thinking of students. Some of the questions asked of students include:

1. What kind of strategies did you apply to solve this problem?
2. What knowledge do you think you have to solve this problem?
3. How have your perceptions about engineering work changed following your engagement with a problem typology framework?

Of interest is to examine the discussion from a range of students from multiple disciplines to support comparison on how they think about design. Further, we seek to understand how that thinking might change over the course of a semester-long project – based on a different extracurricular problem – that they are working that includes discussion of engineering problem types and reflective activities as educational interventions at set points in the project experience.

This form of data collection, involving students from multiple disciplines, across multiple years (sophomore-senior) brought into sharp focus the challenge of developing a suitable problem statement. It has been argued and shown that there are gaps between the question being asked and the question that students think they are answering among math students [23]. Our work is toward capturing similar evidence among engineering students.

The problem framing attributes are defined below for design problems based on [6] and considered in the context of the design problem in Appendix A. These represent important aspects of problem framing that are specifically considered in the development of our problem statement.

Learning Activity

This attribute focuses on the learning outcomes for the problem type. The primary learning objective for design is to drive action around goals toward production of an artifact. Problem structuring and articulation are important aspects of the learning activity.

In our problem the scenario posed to students is for the design of "sustainable playground equipment." Specifically, students are challenged to design playground equipment that when used generates energy. This problem was adapted from a prior design study [38] through more careful consideration of the problem attributes from [6].

Inputs
For design a vague goal statement with limited constraints is needed. For our problem to "develop playground equipment designs" is the vague goal and constraints are not specified, though suggested sources of constraints come in the form of "appropriate safety standards."

Succcess Criteria
Success criteria should be multiple but not specifically defined. There is not a right or wrong answer but potential to measure better or worse is important. As a design problem, where ill-structure is the norm, learning is not measured by efficiency of achieving a solution, but instead by decision-making processes and related argumentation.

Success criteria for our problem are relayed as feasibility to produce appropriate levels of energy, though what constitutes an appropriate amount of energy is not specified. Further, while energy generation would serve as a primary measure of success, it is dependent on other secondary success criteria, like the "demand" for use of the equipment by children, which is not an obvious consideration from the description. Instead, this is the type of criteria that we expect to be "discovered" as part of the group discussion and planned inquiry.

Context
A complex and real world context is important as it speaks to authenticity and offers degrees of freedom in the solution path. Where well-structured problems can de-emphasize the role of context, ill-structured problems, like design, require consideration of context if we seek to facilitate students' consideration of a wider range of social, economic, and environmental issues.

Context in our problem is conveyed through multiple modalities. First, the text and pictures indicate that the intended user group lives in the developing world and provides visual evidence to help students differentiate their own classroom experiences with the types for which they are designing. Additionally, we provide a map and local connections to situate students (many of whom may not be local to Buffalo) relative to the local support and extended development team. This is to provide them a reassurance that although they are developing a solution for an unfamiliar place they can still draw from local context as part of thinking about solving the problem.

Abstractness
This refers to domain specificity and for design, is inherently "problem situated". That is, the nature of the problem as specified in terms of inputs, success criteria, and context, will dictate the knowledge domains necessary to the problem. This is important in driving the types of information and expertise that students seek in structuring and developing solutions to the problem.

For our problem, the abstractness occurs on two dimensions. On one dimension is the type of equipment to be developed – playground equipment – for which the students can likely relate based on personal experience on playgrounds. Similarly, there is consideration of energy generation, where again students can relate based on knowledge of where and how energy in the developed world is generated. Though they likely lack experience designing an artifact that leverages knowledge from these domains, the knowledge domain is not so abstract that students would be unable to think about the problem.

On the other hand, specific knowledge of conditions in the developing world are likely to be outside of the student experience. Here, the inclusion of Engineers Without Borders is intended to provide reassurance in the form of a source for better understanding the specifics of the use environment. Similarly, pointing to a design partner in the form of a local playground equipment manufacturer and local schools as test sites is to provide the students with resources that can better inform their solution process.

Our study is concerned with the development of metacognitive strategies of students and how problem typology can be central in developing professional competencies. If we consider the formal design process, the goal is to provide a series of stages that help engineers in moving from a qualitative problem representation to a quantitative representation that facilitates engineering a solution.

We are currently gathering data from various problem solving events and reflective interviews with students to inform students' use and understanding of problem typology. Our mixed methods approach will use epistemological, professional, and experiential inventories to triangulate with interviews to qualitatively analyze student thinking and shifts in their use of typology as an organizing framework for engineering problem solving.

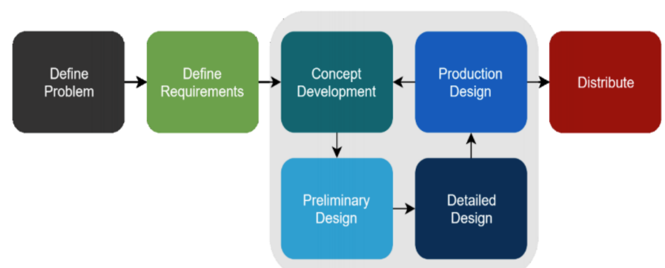

Figure 1. Design process diagram used for student discussions and reflection activities

As we are exploring different problem types, we plan to consider various forms of discourse [39, 40] of student discussions. More specifically, through discourse analysis, student discussions are being coded and mapped to the individual stages of the design process diagram of Figure 1. Of interest is to see how the discussion reveals the ways in which students (i) orient themselves to open-ended problems, like the design problem in the Appendix; (ii) where they start their problem solving (e.g. do they jump right to developing concepts?) and how that might compare with experts or accepted best practice in design; and (iii) the way in which the discussion traces the design process (e.g. does discussion jump around the stages? how much? for how long? does a pattern of iteration emerge?).

CONCLUSION AND FUTURE WORK

The work presented here represents a small part of a larger research project. However, it is a significant issue as our ability to assess students' design thinking is dependent on careful formulation of the design scenarios we construct. In the near-term we expect this investigation to provide greater insights that are useful to our research and possibly the research of others.

Beyond the formulation of a design problem, this investigation extends to the formulation of engineering case analysis scenarios. We are currently developing engineering analysis problem statements and planning to analyze resulting student discussions around those statements following approaches similar to that described in this work. Namely, mapping of coded discussion with students onto a specified process framework for engineering analysis. In time, we plan to continue this investigation into other common engineering problem types, like troubleshooting and planning problems.

While serving a minor role now, in the long-term we believe the outcomes of investigating this topic could have significant implications for design education and engineering education more broadly. Careful consideration of problem formulations that seek to accommodate the multiple characteristics that describe problems may lead to the development of a data base of engineering problems. These problem statements could be used as a basis for capturing a range of data related to how engineering students think about and solve problems. Facilitating such data collection across a variety of institutions and disciplines would be helpful to developing strong assessment criteria for evaluating students and informing engineering curricula.

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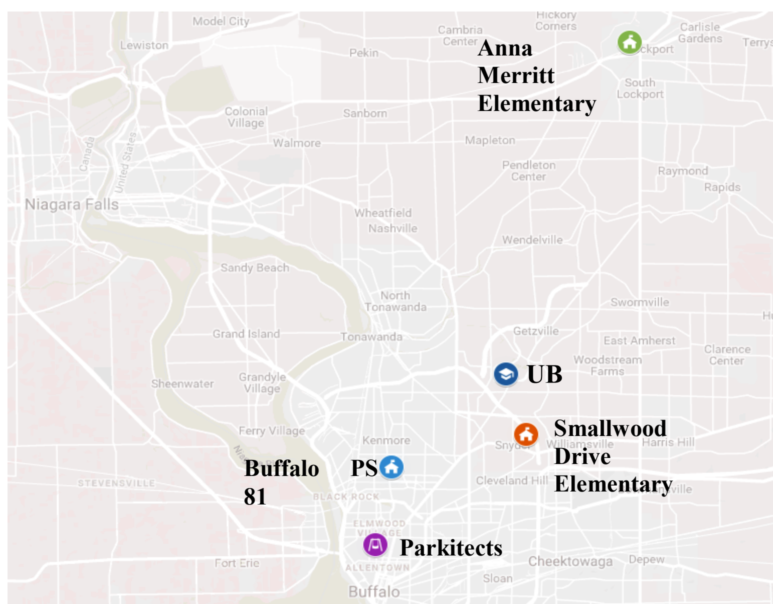
APPENDIX A: EXAMPLE DESIGN PROBLEM DESCRIPTION

Sustainable Playground Equipment Design

Developing countries face significant challenges in energy production due to the lack of supporting infrastructure. The lack of access to energy impacts many aspects of life, but a specific area of need is providing energy for schools. A little bit of energy can have a significant impact on education in the developing world by providing energy for lighting to extend school days, fans to cool the school house, and atmospheric water generators to provide drinking water.

A local playground equipment manufacturer – Parkitects – is working to develop a “sustainable playground” that could harvest energy from use of the equipment. UB Engineering students have been recruited to the project team. The project is being done in collaboration with Engineers Without Borders. The equipment will be included as part of an energy generation package that includes solar panels. Of course, the equipment package could be limited to solar panels, but the project motivation is to provide both energy generation capability, and equipment that supports other aspects of the children’s development.

As part of the development process, Parkitects is partnering with local schools to design and test equipment prototypes. Three local elementary schools have been selected – Smallwood Drive Elementary in Amherst, Buffalo PS 81 in Buffalo, and Anna Merritt Elementary in Lockport – and will participate as part of the design and testing process over the next 18 months.



Your team is expected to develop playground equipment designs that could be part of a sustainable playground. Your team should:

- Consider appropriate safety standards for playground equipment
- Ensure that the product is capable of producing sufficient energy to be a feasible consideration
- Document selection and rejection of design concepts
- Consider the most relevant factors/requirements that influence decision making