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Developing an Interview Protocol to Elicit Engineering Students' Divergent Thinking Experiences

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Abstract

As problems become more complex, global, and interdisciplinary, engineers need to develop novel solutions and utilize resources, information, and tools in strategic and creative ways. Divergent thinking describes a process where multiple options, pathways, alternatives, or ideas are developed. For engineering students, divergent thinking can facilitate flexibility and expand opportunities considered when solving problems. To develop divergent thinking skills in engineering, we must understand how it is (and is not) facilitated in current engineering education experiences. Current pedagogy and resources available in engineering education on divergent thinking are limited. Thus, our research focused on exploring educational experiences in which students felt they considered divergent thinking. In this paper, we describe the iterative development of an interview protocol to elicit student experiences related to opportunities for divergent thinking. From the initial round of piloting, we found student awareness of divergent thinking was limited. Our findings highlight the need to structure questions in ways that align with students' existing understandings of their engineering experiences. Our team made modifications to the protocol to address this, including using accessible terms to describe divergent thinking, asking students to describe one example project they remembered well, and focusing questions within one step of the project selected by the student as most relevant to their exploration of alternatives. This iterative development of the protocol was successful in eliciting divergent thinking experiences across their work.

Introduction and Background

Engineers are expected to solve problems in innovative and novel ways as articulated by various engineering education organizations [1], [2], which can be achieved by creatively approaching problems. Creative thought includes both convergent and divergent thinking [3]. Engineering students traditionally are taught problem-solving skills and knowledge that prioritize convergent thinking, which is based in logical reasoning, analysis, and evaluation to narrow down options [4], [5]. Divergent thinking engages in the process of exploring alternatives and multiple diverse options. While convergent thinking is an important and valuable part of problem-solving, divergent thinking creates options necessary to make choices down the line and facilitates more opportunities than otherwise would have been possible without it [6]. Divergent thinking can occur at various stages and ways in engineering problem-solving, such as in the types of research gathered, consideration of stakeholders, understanding of problem contexts, methods to approach the problem, and considering wider project implications of engineering decisions. For example, students might consider multiple experimental methods to answer a research question or explore the potential implications of their design decisions. Research has shown divergent thinking allows engineers to think more creatively, identify new opportunities, increase reasonable risk-taking, and consider broader types of solutions [7], [8]. By engaging in exploration of alternatives during engineering processes, engineering students can think flexibly and in different ways to be better prepared to solve global problems and adapt to changes and new developments in society.

Divergent thinking is an underdeveloped but critical skill that engineers need to solve complex problems. While engineering instructors want students to engage creatively in their work, they have expressed discomfort in supporting students in exploration, and students feel they have limited opportunities to engage in creativity in engineering [9]. Currently, opportunities for divergent thinking in most engineering pedagogy is limited to open-ended design projects, for example in first year engineering or capstone design courses [10]–[12]. However, even with opportunities to diverge, students may not be taught or facilitated in using specific strategies for divergent thinking throughout their engineering problem-solving experiences. Education that exists on divergent thinking in engineering often centers only on idea generation and considering many varied solutions [13], but in practice there are many other opportunities during engineering problem solving for students to think divergently. Moreover, engineering course rubrics and evaluations, which students rely heavily upon as an indicator of what is important within a course, lack evaluation and feedback about divergent exploration across problem-solving activities [9], [12]. This absence of criteria to evaluate divergent thinking indicates a lack of intentionality and value for divergent thinking and can be a potential place of growth in skills for engineering students. This indicates a need for curriculum and tools to support divergent thinking, and a need to support engineering instructors to incorporate divergent thinking learning goals, pedagogy, and assessment intentionally and strategically in their courses.

Interview Protocol Development and Piloting

Our research focused on exploring student engineering education experiences in which students felt they were supported and hindered in divergent thinking. We describe the development of an interview protocol to elicit student experiences of engaging in divergent thinking, present data from student interviews that informed the final protocol, and highlight ways divergent thinking was evident across their work. This process overview is shown in Figure 1 below.

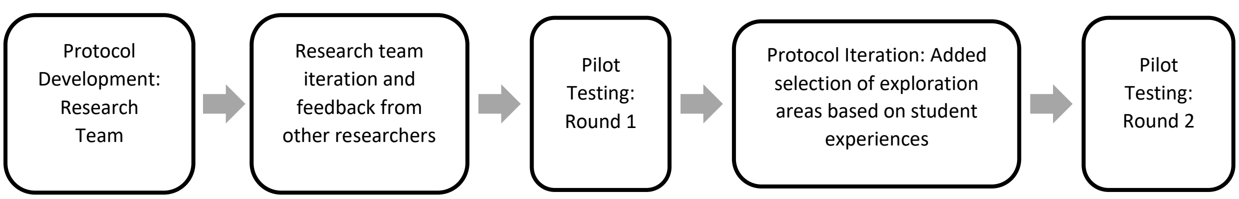

Figure 1. Protocol development process

Protocol Development: Research Team

Since "divergent thinking" is not a common term in engineering education, eliciting student experiences, opportunities, and obstacles required some scaffolding. While developing our interview protocol, we had to be intentional and explicit about the language, questions, and how we elicited student experiences to specifically target divergent thinking experiences beyond idea generation of solutions. Thus, early in protocol development, we decided to use more approachable language than "divergent thinking", such as *explore alternatives* and *consider multiple options or perspectives*. We developed an interview protocol to support students in unpacking multiple aspects in which divergent thinking could be possible in a wide range of engineering work. The interview protocol for this study was developed through multiple rounds of iteration and to investigate student experiences in divergent thinking across various engineering activities. Question structures were guided by recommended practices in qualitative research, focused on gathering rich detail and examples [14] in this case of divergence in various aspects of engineering problem-solving. The first stages of iteration were internal to the research team, where we drew on divergent thinking literature, expertise on creativity, and our research questions. We were interested in consideration of alternatives in multiple areas of engineering activities beyond just solutions. We aimed to answer the following research questions: 1) How do engineering students bound and explore alternatives? 2) How do engineering students self-assess their exploration of alternatives? and 3) What cognitive and perceived environmental factors impact bounding and exploration of alternatives?

We began with five sections of questions in this early version of the protocol based on our research questions: 1) concrete experiences, 2) problem definition, 3) exploration of potential solutions, 4) work environment, and 5) comparison to other experiences, as shown in Table 1. We chose to ground our data collection in students' concrete experiences [15], so first we asked about the student's background, previous experiences, and the context and description of one engineering project. Relative to this project experience, we asked more in-depth questions about their exploration of alternatives through defining the problem (section 2) and exploring potential solutions (section 3) in their engineering problem solving. Next, we asked about the work environment to understand supporting and hindering factors to divergence. Finally, we asked students to compare the concrete experience they shared to another previous experience to gauge how typical their experience of exploration was to their other experiences.

Table 1. Descriptions of each area of exploration for the initial protocol

Protocol Sections	**Section Content**
Concrete Experiences	• Background of the student • Introduction to one engineering project: inquiring at a high level "a single experience working on an open-ended engineering project in which there was not one right answer, but instead multiple possibilities." • Follow up questions: dive deeper into the structure of the student's organization, the project team, the student's role on the project, and the constraints of the project, context, and topic
Problem Definition	• How the project was originally defined • Information gathered for the project • What was necessary to consider in the project • Stakeholders for the project and how they changed over time • How the student explored in this area and their understanding of the problem changed over time
Exploration of Potential Solutions	• How the student generated potential solutions • If they considered more than one solution • How the team communicated with each other and to the larger structural organization/stakeholders • Specific examples of solutions they included or did not and why
Work Environment	• Aspects of students' work environment that felt encouraging or discouraging of exploration
Comparison to Other Experiences	• Comparison to another open-ended project with similarities and differences in reference to the original project • Ways in which the student felt more or less explorative • Overarching questions about what it looks like to be successful at exploring alternative possibilities • Which parts of their training and experiences helped them most in exploring problems and solutions • Past experiences or knowledge outside of engineering assisting them in exploration

Protocol Iteration: Feedback from Outside Researchers

After reviewing the initial protocol among the research team, we added sections about students' problem-solving approaches and potential project implications, as well as separated questions about information gathering and stakeholders from problem definition. These decisions were made to capture more in-depth context and explicit examples about the involvement of stakeholders, problem-solving approaches, and implications of project decisions made. Next, we solicited feedback from a group of engineering and design graduate student researchers with experience in interview protocol development about the structure, language, and intent of the questions and overall protocol. Feedback focused on the length of the protocol, the wording of certain questions, and language choices to facilitate students in discussing divergent thinking in mechanical engineering problem solving. We made more changes to incorporate the feedback given about the protocol.

Pilot Testing: Round 1

After updating our protocol, the next rounds of iteration were informed through conducting two semi-structured interviews with mechanical engineering students. Our focus during these pilot interviews included the extent to which students were able to share diverse experiences engaging in divergent thinking, and what structures and factors encouraged or limited their engagement. Students were recruited through research team networks at a large Midwestern university. The two students were selected intentionally to have some variation in their prior experiences, co-curricular involvement, and coursework. Both students identified as white women: one was in her second year of a mechanical engineering degree program and the other in her fourth year of a mechanical engineering degree program. Interviews were audio recorded and transcribed for analysis.

During Student 1's interview about her senior capstone design, the descriptions of potential solutions were addressed earlier in the protocol while discussing problem understanding because her understanding of the problem shifted and evolved during the idea generation and prototyping activities of her project.

> Q: "Do you have any examples of different ways that you understood the problem as you were going through the project?"
>
> A: "So, in the beginning it was just broad concept because they already had a tag developed with the electronics. And so, in my mind, it was going to be like **Okay, how do we take this tag that already exists and stick it on [animal] and then from like thinking about that conceptualizing prototyping. We kind of realized that the tag wasn't actually doing to work at all and we'd have to redesign the electronics housing so then it turned into a problem of like Okay, how do we redesign the electronics housing attachment mechanism**…so design and attachment mechanism so there is less drag, like focusing on the size of the thing and shape of it, and the drag of it."

Student 2 described her international project to design a seating device for children with cerebral palsy and how her problem understanding shifted during a later phase of the project when the team engaged with more stakeholders:

> Q: "How has your problem understanding changed over time?"
>
> A: "[Previous year's team] did the initial, like, needs analysis when they traveled to [Central American country]. And, initially, I believe, like last year when they were just like randomly prototyping things, I think the original idea was something along the lines of a like a beanbag chair and it definitely **I think took a very different turn over the summer, when [the local stakeholders] were like this isn't like really what we're going for**. **And then from there talking more with the partners, it took another turn**

> **to being you're not just making this for two specific kids, you're making this for 30 kids** and we're making more of a modular kit that can be adaptable for all the kids…"

Rather than proceeding with their original design solutions, this student described having to go back to the stakeholders to gather more information about the problem and then re-thinking their original understanding of the problem. Thus, exploration of solutions was not explained by this student in the same way as the first student where her problem understanding changed with their exploration of solutions.

These pilot interviews revealed that we needed to make the protocol more flexible to account for discussions students had about their projects where they engaged in multiple activities within a problem-solving area of exploration. In addition, time was a concerning factor during the interview as originally slotted for an hour, but interviews took up to an hour and a half and still not every section was covered during the interview, or some questions were cut short because of it. Using this data, we decided in the next version of the protocol to allow students to begin by choosing which exploratory sections felt most relevant to their engineering project, rather than ask about every problem-solving area. If time permitted, the interviewers could go back to other sections to ask about the student's divergence in other areas. We hoped these changes would help us to capture experiences in-depth while adapting to the wide variety of project experiences and discussion timing ranging across research, curricular, co-curricular, and industry projects.

Protocol Iteration: Student Selection of Exploration Areas

We implemented the updated protocol as shown in Figure 2. Each student was asked introductory questions about their background, previous experiences, and chosen project overview; then, interviewers stated, "We're interested in engineering project experiences where you either explored multiple options or perspectives in one or more areas of the project, or you think the project could have benefitted from exploration but something about the situation limited your ability to do so." After this, we listed and defined of each of the subsections (1-5), as shown in Table 2. Students chose which subsections felt most relevant to the engineering project they had selected. This allowed interviewers to start with the exploratory area and questions that were most relevant to the student's experience, then go on to other subsections with time permitting.

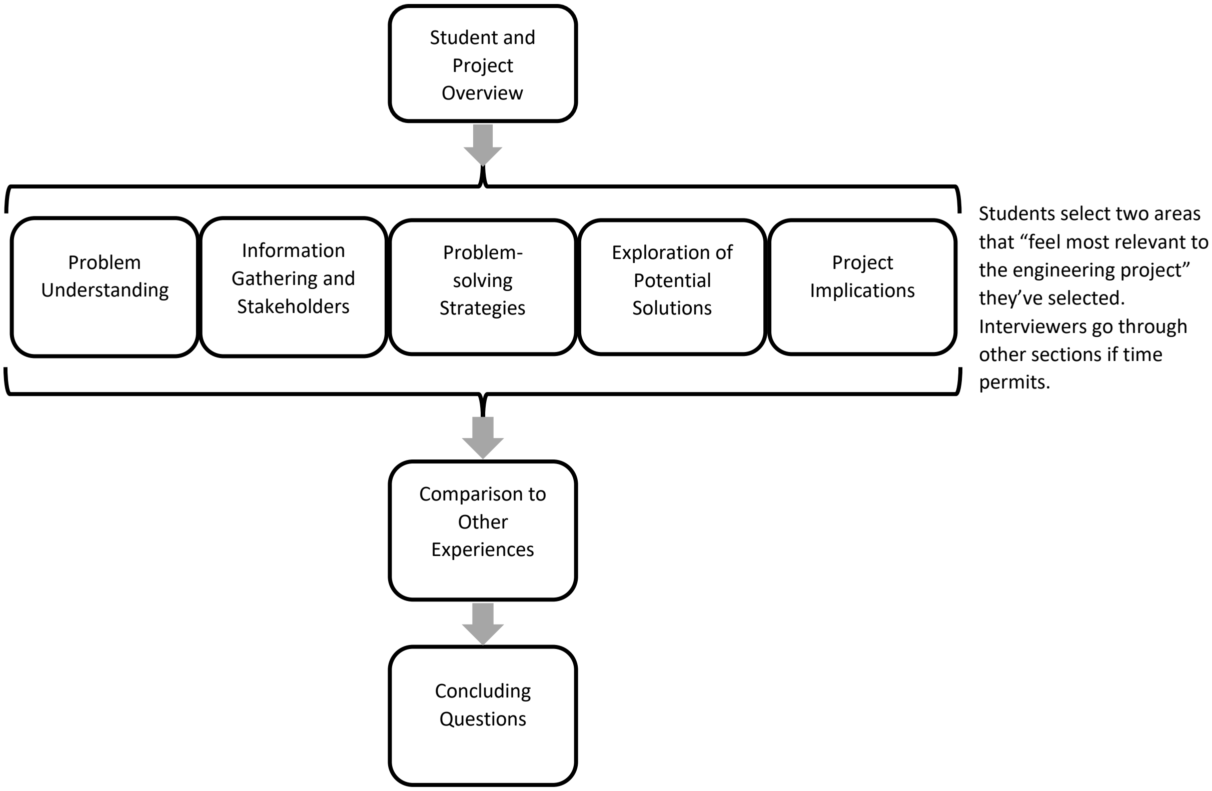

Figure 2. Final protocol overview and section order

Table 2. Areas of exploration options to choose from and definitions given to students

Areas of Exploration	**Section Definition**
1) Problem Understanding	What you knew about the context you were working in and the goal of the project
2) Research: Information Gathering and Stakeholders	Information gathering (about prior work, user context, experimental methodology, etc.) and stakeholder consideration
3) Problem-Solving Strategies	The activities or methodologies you chose to work towards a solution
4) Exploration of Potential Solutions	Solutions you considered throughout the project
5) Consideration of Implications	Impacts on people or environments of the project solution or a decision made while working on the project

We identified these five areas in engineering projects where exploration may occur to encapsulate a wide variety of engineering problem-solving activities across multiple types of engineering work. We utilized and synthesized information from design process models, e.g. Dym's design process model [16], systems thinking work, e.g. the Vee model of systems development [17], problem-solving techniques, e.g. use of modelling and simulation technology [18], and other engineering problem-solving process models and characteristics, e.g. everyday problem solving in engineering lessons learned [19], to capture common stages and aspects of engineering work. Language around the project also changed with this iteration. We asked students to tell us about a project that was *successful* rather than *open-ended* to accommodate engineering students who might not necessarily see their work as open-ended or capture multiple types of engineering work that may have set constraints or problems. In addition, we wrote definitions for each subsection title and developed examples in case students were not familiar with terms such as 'stakeholder identification' or 'problem understanding.' We broadened the language in some places in the protocol, for instance, changing from *problem definition* to *problem understanding,* as problem definition is often language used in a design context, but we wanted to evoke stories of engineering experiences more broadly.

Our final protocol structure for the five areas of exploration (problem understanding, research, problem solving strategies, potential solutions, and project implications) were the following:

1. What did you do?
2. How did you decide to do that?
3. What alternatives did you explore?
4. How did you know you had explored enough alternatives?
5. What alternatives did you not explore?
6. Why did you not explore those?
7. How successful were you at exploring?

Pilot Testing: Round 2

We piloted this final protocol in semi-structured interviews with two more engineering students. As in the first round of piloting, students were selected through research team contacts from a larger Midwestern university and were selected to have variation in their project experiences, co-curricular involvement, year, and identities. Student 3 identified as Hispanic woman in her fourth year of mechanical engineering and Student 4 identified as an Indian woman, undeclared as a first-year engineering student.

Student 3 stated her project had limited exploration due to the nature of the class project competition in her second-year design course, whereas Student 4 described her coding project having both a pre-defined problem and final solution. Student 3 selected Problem Understanding, Research: Information Gathering and Stakeholders, and Problem-Solving Approaches while Student 4 chose Exploration of Potential Solutions, Problem-Solving Strategies, and Research: Information Gathering and Stakeholders. The flexibility of the protocol allowed the students to focus on areas during their problem-solving processes where they explored most, which allowed for them to go into detail and give specifics about where they diverged during their projects. For example, Student 4 revealed they did not explore during all aspects of their engineering project; rather, it depended on the context and structures surrounding the project.

> Q: "How did you decide when you had explored enough potential solutions?"
>
> A: "**I didn't necessarily develop the initial problem statement** and the challenge on my own, it was kind of given to me. A lot of times I would run into issues where I would have multiple things that needed to happen at the same time within each other…**It's very clear when you've kind of solved your problem and so, for me, I stopped exploring different solutions when my final solution gave me the correct answer…"**

The student knew the solution they needed to solve their problem to accomplish a certain task with the code, so they didn't need to explore alternative solutions. Instead, they heavily explored strategies to solve the problem and the information they needed to gather. By implementing the changes to the protocol, we were able to capture project experiences with non-open-ended problems and specified constraints due to the course project guidelines that showed how divergence can occur in other parts of the experiences.

Discussion

We followed a protocol development process leveraging best practices in qualitative research, expertise in engineering and creativity, feedback from fellow researchers, and data-informed iterations. The changes to our protocol internal to the research team and feedback from other researchers with engineering and interview development experience included more understandable language around divergent thinking and expanding areas of exploration to include explicitly a section on information gathering, stakeholder engagement, problem-solving strategies, and project implications, in addition to timing, length, and structure. The first round of piloting caused changes to how the protocol would be used with students selecting areas of exploration that were most relevant to their chosen project experience, solidifying timing, capturing divergence in a broader range of engineering project types, and flexibility to each student's experiences. The next iterations of the protocol also included defined areas of exploration to have a mutual understanding between the student and interviewer as well as consistent question structure within each area of exploration focused on what was done, how decisions were made, when they knew exploration was finished, what they didn't explore and why, and overall, how that student rated their success of exploration in that area.

Using this finalized protocol, we captured in-depth experiences of divergence within more structured engineering course projects and revealed how divergence may occur in the process. Major themes to divergence included when problems are rigidly defined, exploration occurred through different strategies to solve the problem and diverse types of information gathered. In addition, students discussed engagement with various stakeholders to better assess competing needs, feasibility, and implications of how the contexts and problem affects the stakeholders' everyday life. Some barriers to divergence included limited time and lack of resources available or known to the students to engage in exploration of alternatives.

Some limitations of this process included limited diversity in the pilot sample, including mechanical engineering students from a single university. The convenience sampling of students through research team contacts may have resulted in students more interested in reflecting on engineering work. Next steps within the larger research study include plans to intentionally recruit a more diverse student sample through program listservs, student organizations, and multiple universities to ensure diversity across gender, race and ethnicity, experiences, and selected projects. The larger research study will be expanded to include high school students with engineering projects as well as practitioners with varying expertise and industry experiences to compare how opportunities for divergent thinking differs across these groups.

Conclusion

This paper demonstrates the importance of an iterative process in protocol development. After multiple rounds of development, an adaptable and scaffolded protocol emerged for understanding divergent thinking in engineering work. The protocol was successful in capturing a variety of experiences and multiple ways in which divergence shows up during students' engineering projects. Pilot interviews showed some potential findings to explore in the larger study, such as divergent thinking while gathering information, potential solutions, and problem-solving strategies. Potential barriers to exploration also emerged, including time limitations, preset problems and solutions, and limited access to other potential stakeholders, resources, and information.

This interview protocol may be adapted for other research questions across multiple engineering and STEM disciplines to elicit students' experiences. Asking students to describe their engineering experiences has the potential to reveal the impact of projects beyond their intended pedagogical lessons. Students' reports create an opportunity to develop a deeper understanding of how students understand and think about their engineering projects. Given that instruction on divergent thinking in engineering education is currently sparse, the new knowledge gained from this protocol will allow us to identify the ways in which divergent thinking is or is not occurring in engineering students' educational experiences.

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