Board 204: Barriers and Supports to Divergent Thinking in Engineering Problem-Solving: An Engineering Student Project Experience

Shannon M Clancy, University of Michigan

Shannon M. Clancy (she/they) is a Ph.D. candidate in Mechanical Engineering at the University of Michigan. She earned a B.S. in Mechanical Engineering from the University of Maryland, Baltimore County (UMBC) and an M.S. in Mechanical Engineering from the University of Michigan. Her current research focuses on idea development and ideation tools, divergent thinking, and engineering curricular practices and culture. Her research interests include front-end design practices, sociotechnical knowledge and skills in engineering, and queer student experiences in engineering. Their work is motivated by their passion for and experiences with inclusive teaching and holistic mentorship of students, seeking to reimagine what an engineer looks like, does, and who they are, especially for queer folks, women, and people of color, through empowerment, collaboration, and co-development for a more equitable world. Shannon is also a Senior Graduate Facilitator and Lab Manager with the Center for Socially Engaged Design.

Dr. Shanna R. Daly, University of Michigan

Shanna Daly is an Associate Professor in Mechanical Engineering at the University of Michigan. She has a B.E. in Chemical Engineering from the University of Dayton and a Ph.D. in Engineering Education from Purdue University.

Dr. Colleen M. Seifert, University of Michigan

Colleen M. Seifert is an Arthur F. Thurnau Professor in the Department of Psychology at the University of Michigan. She received her Ph.D. in psychology at Yale University. She was an ASEE postdoctoral fellow at the University of California â€" San Diego

Barriers and Facilitators to Divergent Thinking in Engineering Problem Solving: An Engineering Student Project Experience

Abstract

Engineering requires innovation to solve complex challenges. Creative solutions require divergent thinking– the consideration of multiple alternatives– in addition to ultimately converging on a single correct solution. Few studies have focused on the impact of engineering education, structures, resources, and environments on students' exploration of divergent options. While often considered during design concept generation, divergent thinking can be pursued throughout engineering projects– when building an understanding of a problem, gathering information and considering stakeholders, choosing problem solving strategies, evaluating possible solutions, and predicting implications of decisions. This narrative study describes one student's experience in an open-ended project, highlighting barriers and themes related to project structures and environments. We identified varied influences on divergent thinking during the student's engineering processes, such as mentor guidance and support of exploration, the participant's knowledge and skills, scholarly research, and material resources. These findings suggest attention to structural support as well as resource accessibility and availability for divergent thinking may be effective in encouraging divergent practices during open-ended problem solving. The narrative serves as a tool for educators, students, and practitioners, emphasizing the importance of environments and structures in promoting divergent thinking practices in engineering.

Introduction

Engineers can help address societal problems through the development of innovative sociotechnological solutions [1]. Common in an engineers' training is learning mathematical and scientific methods, where there are often specific, detailed processes, and problem sets that converge to a "right" answer [2], [3]. Engineering training also includes skills to navigate open-ended problems, such as a design challenge, where there is not a single right answer. Through these open-ended engineering projects, there are opportunities for engineers to navigate ambiguity and consider multiple options. However, there is often little structure and guidance to support engineering students in engage in divergent thinking– the exploration of multiple perspectives, options, or alternatives [4]---during this work, for example, to take risks, consider multiple perspectives or disciplines, and explore many solution pathways [5], [6].

Given current pedagogical limitations of tools and resources to facilitate divergent thinking throughout a problem solving process in engineering education, the goal of our work was to understand current environmental and structural factors that influence engineering students' engagement in divergent thinking during open-ended problem solving. In this paper, we focused on one student's experience to dig into the complexities of her project, surroundings, and decisions and leverage the power of storytelling. By examining factors that influence engineering students' engagement in divergent thinking, the outcomes of this work can support instructors in proactively structuring projects, structures, and environments to promote students' divergent thinking.

Background

Divergent thinking in engineering education has predominantly focused on the generation of solutions. A common ideation goal is to generate as many ideas as possible [7], and various tools, such as such as Design Heuristics [8], Morphological Analysis [9], and TRIZ [10], exist to support the diversity of these ideas and to overcome early attachment to a single idea [11], [12]. While divergent thinking is important in ideation, it is also important to multiple other aspects of problem solving. For example, problem exploration includes considering different possible ways to focus the problem definition based on information gathered [13], [14]. In addition to divergent thinking informing possible solutions and possible problem understanding, divergent thinking is beneficial throughout a problem solving process, such as determining what information to gather, what stakeholders could impact or be impacted by project outcomes, what problem solving strategies to use, and what implications might occur for potential decisions.

Divergent thinking can be beneficial to open-ended problem solving in many ways, and the extent of this divergence can be influenced by external environments and resources [15]. For example, giving students options of activities and choice agency, incentives for risk taking, and providing flexible directions and listening to and affirming ideas of students by mentors or teachers can cultivate supportive climates, all of which are important for creativity [16], where divergent thinking plays a major role in more creative outcomes [17], [18]. Scaffolded and structured divergent thinking tasks grounded within a discipline such as engineering, rather than just general training, with explicit guiding instruction can boost problem-solving capabilities [19], [20].

Greater evidence through stories or other methods of successes and failures of divergent thinking within engineering contexts can help build critical thinking skills, diversity of thought, and engage in engineering in new ways. Divergent thinking studied within an industry setting has been shown to be beneficial for engineers to know how their work in their specific context fits within larger systems and with decisions and specifications rooted in that context [21]. Stories and reflection have been used to develop engineering literacy through contextual awareness for sociotechnical problem solving [22], [23], [24] and creative engineering skill building more largely [25], [26]. Given this, having stories that are useful for students, faculty, and even practitioners to reflect on barriers and promoters of divergent thinking in engineering may help foster encouraging environments, provide contextualized support and resources, and be an educational tool for more creative outcomes.

Methods

The goal of this work was to describe in depth and contextualize barriers and facilitators of divergent thinking for one engineering student. We selected one student to provide an outcome that read as a narrative or story, which serves as both a research deliverable as well as an education deliverable to support instructors in facilitating divergent thinking.

Data Collection

We collected data through an interview with one student to use for a narrative. The interview data for this study was drawn from a larger data set collected as part of a project about mechanical engineering students' and practitioners' divergent thinking experiences in engineering problem solving. The interview with the student participant for this study was semi-structured and conducted via Zoom. The interview protocol was grounded in an open-ended engineering project selected by the participant that they perceived as successful. After describing the project in detail including timeline, team members, goals, etc, the participant selected two areas of exploration within a problem solving process from a list: problem understanding, research and information gathering, problem solving strategies, potential solutions, and project implications. More detail about the interview protocol development and piloting process has been documented in a previous conference paper [27].

The participant we focused on for the study described in this paper was chosen for the rich comprehensive description provided, enabling us to demonstrate multiple, diverse examples of barriers and facilitators of divergent thinking. We use the pseudonym Evelyn for the participant, and more information about her is provided in the narrative below, so her information can be kept with the rest of the findings when presented as an educational tool. In her interview, she selected to discuss divergent thinking within problem understanding and problem solving strategies as the most relevant areas she explored in her project.

Data Analysis

The interview was recorded, transcribed, and de-identified for analysis. The first author and a research assistant read through the transcript and wrote detailed memos, following qualitative best practices [28]. These memos included notes describing the participant's experiences and example quotations, questions, potential factors that impacted her divergent thinking, and whether these factors were barriers or facilitators to her divergent thinking. These interpretations we made are based in the context of the situation we know because of the in-depth discussion that was had during the interview. These interpretations were discussed with the co-authors and iterations were made on the findings until agreement. We chose to analyze and write the participant's experience as a narrative to 1) root the findings in the context of her project and 2) elucidate the intersecting influences of her environment on her experiences based on the resources, people, and structures she had available and had to navigate in her problem solving. Narratives are important tools to illustrate inherent complexities and understand important stories in engineering education environments and research [29]. This narrative illuminates different aspects to divergence, and barriers to it, for one student including troubleshooting as a process for divergence, gathering information from various sources, trying different problem solving strategies, leveraging knowledge and experience of mentors and others, and reflections on divergence.

Narrative

Evelyn was an Asian woman and a senior in mechanical engineering at a large Midwestern research intensive university at the time of the interview. She had multiple internship experiences

within the defense and aerospace industries and was involved in various research experiences and a manufacturing engineering project subteam within the college of engineering. She described her most recent internship project focused on updating sensor equipment to improve technician assembly and transportation time as well as reduce bulk on the system.

During her initial work on the project, the plan was for her to design, develop, and test a new sensor enclosure. However, she found an issue with overheating of the sensor that was unexpected both by her and her mentor. Her mentor then encouraged her to explore this issue further. This prompt to explore the unexpected problem provided Evelyn an opportunity to apply divergent thinking in troubleshooting the problem:

> *"I remember when some of these issues started, specifically when the printed circuit board (PCB) started overheating, I immediately turned off the equipment and I had written down all my observations to see what exactly was going on, if there was smoke, which there was, if there was a specific time after things were running, and then I had reviewed those observations. And then from there, I had decided that I needed to take a step back and check what was going on. So I had checked if this issue would repeat itself. I had a couple different spares of this setup anyway. So I had swapped them out over and over to see if the issue repeat itself, whether it was just a pure issue...or just one defective component. And unfortunately it was definitely an issue because all of them had been experiencing the same issue that somehow never got caught before in other tests."*

In discovering this sensor issue, Evelyn took a step back and thought widely of how to approach her work: leveraging observations, testing multiple devices, and asking herself multiple reflective questions about the system and her process to explore the problem at hand and understand what was going on. She explored her options first before jumping directly into a conclusion as an initial key step to divergent thinking in her problem solving.

Evelyn also explained her feelings of uncertainty and ambiguity around this problem during her exploration given her limited knowledge and experience with circuits, both limiting her ability and pushing her to explore more herself and leverage others' knowledge:

> *"It was definitely a mechanical side of thinking at first, is it on my end? Because from what I heard, it worked before it got into my hands. And then when I realized there was no way it couldn't have been, I started looking into the electrical side, which I knew was a little scarier for me, because I just did not have that experience. I didn't know 100% what I was doing. So I think it definitely got a little more intense as I tried going into a field that I felt like... it was kind of when they told me, 'You can work on it and let us know what you see.' I felt it was blind leading the blind of, I really don't know what I'm looking at. But I think I definitely... it was definitely helpful for me to at least try to understand it. And when I realized I couldn't, because it was just something I wouldn't understand in time, something that definitely felt it would take multiple courses to understand. I had just showed it to other electrical engineers."*

Given Evelyn only had one circuits course, she was struggling in the beginning of her problem solving to know how to explore the issue further, at first creating a barrier to her divergent

thinking and how to proceed. Through reflection, she recognized an opportunity to take initiative to gather more information she had access to and more experienced circuitry knowledge of electrical engineers around her, facilitating her divergent thinking in later stages.

Evelyn explored multiple different problem solving strategies in parallel during troubleshooting: reduce overheating and explore the underlying issue. Evelyn took initiative to further her circuitry knowledge given her engineering education did not provide the depth she needed for this problem.

> *"I was running it at different current inputs…put it in a different orientation and see what was causing this specific component to just get so hot. And because I knew that my circuit knowledge was very limited because we only had really one circuits course, and it wasn't as intensive, or it wasn't as involved as it should have been to prepare me for this project. I had to also take a step back and read about general circuitry, why certain things overheat, how you could reduce that. And then when I couldn't figure out why it was overheating, I was also simultaneously, which probably wasn't as efficient, but I figured I'd do it anyways, look for how to keep it from overheating while I was trying to also diagnose issues since at that point..."*

Evelyn combed scholarly papers to gather a diversity of information about the issue in addition to running different types of tests with the sensor in different orientations, current levels, and other various inputs for the sensor, engaging in divergent thinking in her problem solving. She sought to explore her options through testing the PCB in fourteen different ways she and other engineers could think of with the time and resources they had to diagnose the overheating issue.

Mentorship was helpful in guiding her exploration by working with her to create a systematic plan and thoroughly explore the issue before trying to fix it:

> *"It was a lot of me learning to take a step back and not just jumping headfirst into assuming, 'Oh, this is the issue. Let's fix it from here.' And it did take a couple engineers to come up to me and tell me like, 'Hey, you need to take a step back because what you're trying to do is too many things at once, and you need to prioritize. Do this first before doing that kind of thing. Don't look into the issues and how to mitigate it before completely diagnosing the issue, so we can figure out if this is something really... fixing its roots of how bad it is and how we can even take it out, or if it's gonna mess up everything.' So it's a lot of that."*

In this case, multiple mentors recommended she step back from convergently deciding the issue and encouraged her to continue considering different reasons the problem was happening. From supervisor guidance, he helped her write down a course of actions, things to pay attention to, and look out for, which helped guide her exploration process, save time, and be organized to not misdiagnose the issue.

Further, she sought out the knowledge and experience of other engineers around her as a resource to explore more, as well as leveraged material resources to prevent this issue:

> *"I had talked to electrical engineers and we had discovered together that we were misusing the PCB. The PCB design was not meant for this type of sensor development by itself. We needed to find ways to mitigate the heat because for now this is the PCB we had to use based on the time crunch and the time it already went into to getting this PCB in our hands…So I had spent numerous days playing with different heat syncs, playing with different materials to see what was the most efficient way to draw away all the heat and to keep it from overheating…There were definitely some on PCBs that were a little defective. So I had taken all the PCBs to the technicians and I had them inspect them. And they found out that not only was it this one issue was also that some of these PCBs were defective by themselves...So the technicians also took over and said that they would expect each one that I wanted to implement, or incorporate thoroughly…Yeah, that was definitely a lot of changing gears constantly and trying to figure out how to solve this within a fair amount of time and be efficient without wasting too much time. So it was a lot of jumping around and a lot of jumping from engineer to engineer, and technician to technician."*

A major aspect of Evelyn's engagement in divergent thinking and navigating ambiguity was being flexible and leveraging knowledge and experience of engineers around her by providing her options to explore and increasing her learning. Also, she had multiple different materials at her disposal to try to mitigate heat away from the sensor, which enabled her to divergently try different options in her attempts to solve the issue.

Evelyn described how guidance and support to explore from various mentors and engineers were influential in her development of understanding the problem with the part, developing confidence, and her knowledge and skills:

> *"I think it was just a lot of the guidance from my mentors. I think that at first it was me just thinking I can figure this out. And I think it was just my mentors in general, who were the reason I was able to even change my understanding and take a step back and learn everything. It was just them saying like, 'Hey, these are all the things that we think from our experience…' I should be doing. They were empathetic. They were telling me stories of how they were at some point in my shoes, and they were trying to do similar stuff. So, I think it is mostly from the help of other people and their own words of kindness and wisdom, and just trying to genuinely be a good mentor that really changed. At least that was what brought me to change it. I think it was also experiences in general that brought me to change my understanding."*

Her experiences with supportive mentorship shifted her thinking when problem solving to take a step back "*...confront the things that we [are] given and look through them slowly and thoroughly…"*, encouraging exploration of a problem and reflection during the process. Supportive mentorship of navigating the uncertainty and problems she was facing supported her divergent thinking, creating a boost in her self-efficacy and affirming her approaches to divergent thinking. Evelyn described how the environment surrounding her project encouraged her to explore by leaving her comfort zone, learn a variety of knowledge in other disciplines, and be more multidisciplinary in future:

> *"I think my environment…it was mostly electrical engineers with several supporting mechanical engineers. I think it definitely encouraged me to have to leave my comfort zone, because I knew from the very beginning I was going to be working with a group that was more focused in one engineering discipline than the one I specialize in. So I think from the very beginning, I was encouraged to have to pick up these things as I went. And I think that definitely forced me to be a little more learning more about other disciplines from the very first day, knowing that all these words, all this jargon that I didn't understand was always going to be used and I had to just pick it up. So I think it was definitely encouraging. And I also had great mentors around me who didn't major in electrical engineering. There were other aerospace engineers who just taught me as I went, because they could tell that I was confused."*

By being around people in various engineering disciplines, she was able to gather and learn from diverse perspectives she had access to about the technical information regarding the sensor, facilitating divergent thinking in her different ways of approaching the sensor issue and learning from a wide variety of people and engineering perspectives.

While Evelyn described how her engineering education through collaboration and working with others in school has been beneficial in her development of divergent thinking, she expressed that she felt her internship experiences helped her explore more:

> *"I think it was probably more of outside education. I feel at least in [design and lab] classes, the answers were like... I wasn't thrown with as many challenges in terms of problems that just can't seem to be solved. Sure, there would be some homework problems that just made zero sense and would take a while to get through, but I felt experience-wise, [the internship project] forced me to really think out of the box and really grow in terms of being more multidisciplinary and learn to hone my soft skills, like communication. And in general, just other technical skills. So I think those really help... I think it was more outside of education."*

Evelyn mentioned how her internship project allowed her to navigate more ambiguous problems and options where there isn't one right way to solve the problem, or an easy or existing solution, unlike her experience at times within curricular contexts.

Evelyn, in hindsight, wished she would have asked more critical questions in the beginning of her project to get a better understanding of who will be affected:

> *"At the time, I guess I should have asked who are the stakeholders, because it was my first time in charge of an engineering project at a company. And I guess I assumed all the information given to me is all the information I needed, which was very wrong. I should have asked what actually is at stake here? Who's affected by it? How critical is it to have it done by this deadline? How much testing do they need to do when it's no longer in my hands and in someone else's hands**?** So I think I started further understanding the project and its necessity to the launch more and more as I attended more meetings, and more engineers were asking how we were going to integrate this sensor, who needed to be*

involved. And that was definitely when I started getting a full grasp of who's actually going to be affected…"

Evelyn expressed a missed opportunity for her own divergent thinking within her project of gathering more information about the larger context and impact of her work and implications of her decisions. She felt she didn't have a full grasp of these implications until later on in her work, as she didn't know at the time how to gather these perspectives of more people who may have had experience with the issues she found, preventing her from exploring stakeholders. From her reflection of asking these questions in the beginning of her project, she could have gathered more information and explored the stakeholders and implications of her work as areas of divergent thinking and developed a more holistic picture of her problem solving and factors to consider earlier on in her project.

Discussion

Evelyn had multiple ways she engaged in divergent thinking throughout her problem solving and troubleshooting. She explored different problem solving strategies in parallel to explore the sensor overheating issue by trying to reduce the heat given off by the sensor, or fix the root cause of the overheating. She collected a wide variety of information through scholarly research and textbooks, and conducted over ten different tests with the sensor with different levels of inputs, current levels, and orientations in developing her understanding of the problem and issue at hand. Further, troubleshooting has been found to be a desired and useful skill for engineers in industry, requiring divergent thinking as an initial base for the process. Described as "a search for a likely cause through an enormous problem space of possible causes" [30], Evelyn's initial stages of troubleshooting included multiple tests, parallel and sequential strategies to gain information about the problem, and writing down her observations. While troubleshooting can include more convergent thinking with testing and evaluation to fix a problem, troubleshooting needs first consideration of potential causes and even has been defined into steps including exploration of the environment and the problem [31], potentially needing curiosity and creativity to investigate. These potential causes are options available during problem solving, which is what Evelyn leveraged and did during her problem solving that directly engaged divergent thinking.

There were two main groups of factors supporting Evelyn's divergent thinking: 1) context of her situation and 2) access and availability of resources. She was able to explore various options and alternatives, engaged in divergent thinking in her troubleshooting due to the context of her situation. She described how none of her mentors or other engineers had experienced this overheating issue before, didn't know the exact answer of how to solve the problem, and was presented with an open ended problem with no direct pathway of how to explore. The context of her situation provided an opportunity to engage in divergent thinking, but it was because of her access to resources and how they were available to her that she was able to explore options during her problem solving. These facilitators of divergent thinking included mentorship supportive of exploration, a variety of different informational sources and testing materials accessible and available to her, and engineers from multiple disciplines with knowledge and experiences she could leverage to gather a wide variety of perspectives.

The supportive environment of exploration Evelyn was in, fostered by her mentor and other engineers she worked with, was a major promoter of her divergent thinking. Her mentor explicitly provided and continued to foster a foundation for exploration by believing in her capabilities, providing guidance to pursue more options, resources to work with to try and fail over and over again, and encouraging her to learn and improve, to be curious, and search widely. Her mentor and other engineers Evelyn worked with acknowledged she must engage in divergent thinking before converging on decisions to do quality and thorough engineering work and save time and money in the long run of the project.

Through others' modeled vulnerability, shared experiences, and guidance in the difficulties of exploration, Evelyn was able to relate to those around her when she was struggling to navigate the ambiguity and think divergently when problem solving. Psychological safety has been described as a key aspect to feedback [32] and creativity [33] with student initiative, self-efficacy and teamwork. Further, mentors and organizational environments that are open, flexible, and encouraging foster creativity while fear of risk taking, criticism, punishment, and fear of making mistakes inhibits it [34], [35]. Instructors and supervisors play a key role for engineering students to feel comfortable and empowered to take risks, explore, and learn to truly engage in divergent thinking.

Evelyn also recognized some barriers to her divergent thinking, such as limitations to her own knowledge and education around circuitry and sensors, a perception of lacking ambiguous problems in her engineering education, and not knowing she could consider or how to explore stakeholders in her project and the impact of her work early on.

Evelyn's existing knowledge was a barrier in the beginning of her problem solving. It can be understood that in order to problem solve and troubleshoot, there needs to be a certain level of knowledge and understanding someone needs to know their options and explore. Evelyn acknowledged that while she had basic circuitry knowledge to understand sensors, she had limitations of deeper knowledge with circuitry, and even didn't feel challenged *"in terms of problems that just can't seem to be solved"* from her engineering education. Over 99% of textbook problems in theoretical courses, like circuits, are algorithmic [3], which is debatable how much this engages critical thinking in open-ended situations [31]. While it is unreasonable to expect undergraduate engineering students to learn in-depth knowledge around every single technical subject, which often requires higher level degrees, Evelyn faced a barrier of divergent thinking approaching this problem early on and how to navigate the uncertainty and ambiguity of the problem, which she felt wasn't taught in her engineering education. Researchers have noted how theoretical courses such as thermodynamics and circuits need to introduce more ambiguity and real-world open ended problems to improve their problem solving skill development [36], [37], [38], [39], [40].

Evelyn's own reflection and critical questioning, as well from the mentors and engineers around her, in combination with the resources she had access and available to her, were significant in overcoming her minimal technical knowledge potentially causing the overheating issues. Evelyn took initiative to reflect on what information she knew and ask questions about possible causes of the problem. This was the impetus for Evelyn to take action and engage in divergent thinking to further her knowledge and know her options by leveraging multiple engineering experts from

a variety of disciplines to know what options were available to explore further and supplement her knowledge with the resources she had access to when faced with uncertainty. Not all students might have these types of resources around them to assist them in their divergent thinking when unsure of their options, or really know how to figure out what their options are. Evelyn definitely didn't at times, and even in reflection during the end of the interview, Evelyn noted how she should have questioned in the beginning the impact of her project and stakeholders that will be affected. She didn't realize stakeholders and project impacts were an area she might need to explore early on in the project. There is limited stakeholder engagement skills and consideration of social and contextual factors of engineering work taught within curriculum, [41], [42], [43] often relegated to project based courses , and varying in the degree of effective consideration and development of these skills [44], [45]. Developing divergent thinking skills with reflection and critical questioning of who is or isn't affected by engineering work and decisions could be a way for engineering students to consider diverse perspectives [21], but may need explicit guidance and consideration for students to think about its importance to engineering work. Students might need scaffolding and explicit teaching about what options they have available within and around their project contexts, and be taught to think critically about those options especially in uncertain or ambiguous situations.

Limitations

There are some limitations to consider with this work. First, our narrative was constructed based on a one time interview with Evelyn about her project experiences. There were no external measures of this account and information. Another interview with her or other collaborators, other types of data such as project documentation, may have been useful to triangulate the findings and gain perspectives beyond her own perceptions. and which may provide more depth and examples across different project types and more time. Second, at times Evelyn seemed to discuss more generally about problem solving than divergent thinking, so at times there was a lack of deep reflection or explicit connection to divergent thinking within Evelyn's problem solving, which at times made it hard to make connections to divergent thinking.

Implications

Understanding barriers and facilitators to divergent thinking can help provide an initial scaffolding and awareness within project environments to foster consideration of alternatives. Messaging, whether implicit or explicit, of project learning outcomes, emphases during instruction or mentorship, and educational or skill building activities needs to create an environment for engineering students where they feel comfortable, encouraged, and value the importance of engaging diverse perspectives and consider many different options. Project structures and requirements that center and incentivize risk-taking, consider multiple options, and provide sufficient resources to explore are critically important to nurture and enhance the value and development of divergent thinking skills.

Given faculty and industry mentors power and role in decision making in projects, course design, and engineering activities, they need support to incorporate divergent thinking activities and create outcomes focused in divergent thinking, while providing opportunities and fostering agency for students to practice navigating their options within structures and environments and

reflect on their experiences. Additionally, engineering students need tools to navigate ambiguity and further enhance their problem solving skills, which divergent thinking may assist with. We hope this narrative can be used as a learning tool for engineering students, educators, and practitioners to grow and reflect on their own practices and awareness of divergent thinking.

Conclusions

We analyzed and constructed a singular student's narrative regarding divergent thinking experiences as a way to portray the context specific complexities and ambiguities of exploration and problem solving in engineering. Divergent thinking can be fostered throughout a problem solving process, not just within generation of solutions, and it is a skill that must be taught and continually developed when problem solving. By elucidating the barriers and promoters of divergent thinking, we can understand how to create environments, structures, and resources to support engineering students in consideration of options, navigating ambiguity, and comfortability of multifaceted decision making in the face of complex sociotechnical problems.

Acknowledgements

The authors would like to thank Madeline Moening for all her input, thoughts, and assistance with this work. This material is based upon work supported by the National Science Foundation divisions of Engineering Education and Centers in the CAREER program under Grant No. 1943805 and the Graduate Fellowship Program under grant no. DGE-2241144. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References

[1] *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*. Washington, D.C.: National Academies Press, 2005, p. 11338. doi: 10.17226/11338.

[2] J. Mills and D. Treagust, "Engineering education - Is problem-based or project-based learning the answer?," *Australas. Assoc. Eng. Educ.*, vol. 3, 2003.

[3] D. Therriault, E. Douglas, E. Buten, E. Bates, J. Waisome, and M. Berry, "Characterization of Problem Types in Engineering Textbooks," presented at the 2022 ASEE Annual Conference & Exposition, Aug. 2022. Accessed: Dec. 18, 2023. [Online]. Available: https://peer.asee.org/characterization-of-problem-types-in-engineering-textbooks

[4] D. J. Treffinger, G. C. Young, E. C. Selby, and C. Shepardson, "Assessing Creativity: A Guide for Educators," National Research Center on the Gifted and Talented, Dec. 2002. Accessed: Dec. 20, 2022. [Online]. Available: https://eric.ed.gov/?id=ED505548

[5] K. Kazerounian and S. Foley, "Barriers to Creativity in Engineering Education: A Study of Instructors and Students Perceptions," *J. Mech. Des.*, vol. 129, no. 7, pp. 761–768, Jul. 2007, doi: 10.1115/1.2739569.

[6] S. R. Daly, E. A. Mosyjowski, and C. M. Seifert, "Teaching Creativity in Engineering Courses," *J. Eng. Educ.*, vol. 103, no. 3, pp. 417–449, Jul. 2014, doi: 10.1002/jee.20048.

[7] A. F. Osborn, *Applied imagination: principles and procedures of creative thinking*, 3rd, revised ed. Charles Scribner's Sons, 1957.

[8] S. R. Daly, S. Yilmaz, J. L. Christian, C. M. Seifert, and R. Gonzalez, "Design Heuristics in Engineering Concept Generation," *J. Eng. Educ.*, vol. 101, no. 4, pp. 601–629, Oct. 2012, doi: 10.1002/j.2168-9830.2012.tb01121.x.

[9] M. S. Allen, *Morphological creativity: the miracle of your hidden brain power; a practical guide to the utilization of your creative potential*. Englewood Cliffs, N.J., Prentice-Hall, 1962. Accessed: Feb. 23, 2015. [Online]. Available: http://archive.org/details/morphologicalcre00alle
[10] G. Altshuller, *40 Principles: TRIZ keys to technical innovation, extended edition, technical innovation center*. Worchester, MA, 2005.
[11] N. Crilly, "Fixation and creativity in concept development: The attitudes and practices of expert designers," *Des. Stud.*, vol. 38, pp. 54–91, May 2015, doi: 10.1016/j.destud.2015.01.002.
[12] D. G. Jansson and S. M. Smith, "Design fixation," *Des. Stud.*, vol. 12, no. 1, pp. 3–11, 1991.
[13] J. K. Murray, J. A. Studer, S. R. Daly, S. McKilligan, and C. M. Seifert, "Design by taking perspectives: How engineers explore problems," *J. Eng. Educ.*, vol. 108, no. 2, pp. 248–275, Apr. 2019, doi: 10.1002/jee.20263.
[14] K. Dorst and N. Cross, "Creativity in the design process: co-evolution of problem–solution," *Des. Stud.*, vol. 22, no. 5, pp. 425–437, Sep. 2001, doi: 10.1016/S0142-694X(01)00009-6.
[15] S. Schrader, W. M. Riggs, and R. P. Smith, "Choice over uncertainty and ambiguity in technical problem solving," *J. Eng. Technol. Manag.*, vol. 10, no. 1, pp. 73–99, Jun. 1993, doi: 10.1016/0923-4748(93)90059-R.
[16] D. de Souza Fleith, "Teacher and student perceptions of creativity in the classroom environment," *Roeper Rev.*, vol. 22, no. 3, pp. 148–153, Apr. 2000, doi: 10.1080/02783190009554022.
[17] M. A. Runco and S. Acar, "Divergent Thinking as an Indicator of Creative Potential," *Creat. Res. J.*, vol. 24, no. 1, pp. 66–75, Jan. 2012, doi: 10.1080/10400419.2012.652929.
[18] G. Goldschmidt, "Linkographic Evidence for Concurrent Divergent and Convergent Thinking in Creative Design," *Creat. Res. J.*, vol. 28, no. 2, pp. 115–122, Apr. 2016, doi: 10.1080/10400419.2016.1162497.
[19] L. T. B. Tran, N. T. Ho, and R. J. Hurle, "Teaching for Creativity Development: Lessons Learned from a Preliminary Study of Vietnamese and International Upper (High) Secondary School Teachers' Perceptions and Lesson Plans," *Creat. Educ.*, vol. 07, no. 07, pp. 1024–1043, 2016, doi: 10.4236/ce.2016.77107.
[20] J. Teng, X. Wang, K. Lu, X. Qiao, and N. Hao, "Domain-specific and Domain-general Creativity Differences between Expert and Novice Designers," *Creat. Res. J.*, vol. 34, no. 1, pp. 55–67, Jan. 2022, doi: 10.1080/10400419.2021.1997175.
[21] L. R. Murphy, S. R. Daly, T. Makhlouf, and C. M. Seifert, "Board 286: 'Exploring Other People's Mind, Exploring Your Own Mind' —A Story of Divergent Thinking from Mechanical Engineering Practice," presented at the 2023 ASEE Annual Conference & Exposition, Jun. 2023. Accessed: Oct. 11, 2023. [Online]. Available: https://peer.asee.org/board-286-exploring-other-people-s-mind-exploring-your-own-mind-a-story-of-divergent-thinking-from-mechanical-engineering-practice
[22] V. C. McGowan and P. Bell, "Engineering Education as the Development of Critical Sociotechnical Literacy," *Sci. Educ.*, vol. 29, no. 4, pp. 981–1005, 2020, doi: 10.1007/s11191-020-00151-5.
[23] G. D. Hoople and A. Choi-Fitzpatrick, *Drones for Good: How to Bring Sociotechnical Thinking into the Classroom*. in Synthesis Lectures on Engineers, Technology, & Society. Cham: Springer International Publishing, 2020. doi: 10.1007/978-3-031-02116-9.
[24] A. Gupta, C. Turpen, T. Philip, and A. Elby, "Narrative Co-construction of Stances Towards

Engineers' Work in Socio-Technical Contexts," in *Critical, Transdisciplinary and Embodied Approaches in STEM Education*, P. Sengupta, M.-C. Shanahan, and B. Kim, Eds., in Advances in STEM Education. , Cham: Springer International Publishing, 2019, pp. 251–272. doi: 10.1007/978-3-030-29489-2_14.

[25] J. A. Turns, B. Sattler, K. Yasuhara, J. L. Borgford-Parnell, and C. J. Atman, "Integrating Reflection into Engineering Education," presented at the 2014 ASEE Annual Conference & Exposition, Jun. 2014, p. 24.776.1-24.776.16. Accessed: Apr. 04, 2023. [Online]. Available: https://peer.asee.org/integrating-reflection-into-engineering-education

[26] P. Caratozzolo, A. Alvarez-Delgado, and S. Hosseini, "Perspectives on the use of Serious-Storytelling for Creative Thinking Awareness in Engineering," in *2020 IEEE Frontiers in Education Conference (FIE)*, Oct. 2020, pp. 1–9. doi: 10.1109/FIE44824.2020.9273994.

[27] S. Clancy, L. Murphy, S. Daly, and C. Seifert, "Developing an Interview Protocol to Elicit Engineering Students' Divergent Thinking Experiences," presented at the 2022 ASEE Annual Conference & Exposition, Aug. 2022. Accessed: Feb. 16, 2023. [Online]. Available: https://peer.asee.org/developing-an-interview-protocol-to-elicit-engineering-students-divergent-thinking-experiences

[28] J. Maxwell, "Qualitative Research Design : An Interactive Approach / J.A. Maxwell.," Jan. 2012.

[29] N. N. Kellam, K. S. Gerow, and J. Walther, "Narrative Analysis in Engineering Education Research: Exploring Ways of Constructing Narratives to Have Resonance with the Reader and Critical Research Implications," presented at the 2015 ASEE Annual Conference & Exposition, Jun. 2015, p. 26.1184.1-26.1184.20. Accessed: Oct. 12, 2022. [Online]. Available: https://peer.asee.org/narrative-analysis-in-engineering-education-research-exploring-ways-of-constructing-narratives-to-have-resonance-with-the-reader-and-critical-research-implications

[30] A. Schaafstal, J. M. Schraagen, and M. van Berl, "Cognitive Task Analysis and Innovation of Training: The Case of Structured Troubleshooting," *Hum. Factors*, vol. 42, no. 1, pp. 75–86, Mar. 2000, doi: 10.1518/001872000779656570.

[31] P. Rivera-Reyes and R. E. Boyles, "Training in Troubleshooting Problem-Solving: Preparing Undergraduate Engineering Students for Industry," presented at the 2013 ASEE Annual Conference & Exposition, Jun. 2013, p. 23.1261.1-23.1261.16. Accessed: Jan. 05, 2024. [Online]. Available: https://peer.asee.org/training-in-troubleshooting-problem-solving-preparing-undergraduate-engineering-students-for-industry

[32] C. E. Johnson, J. L. Keating, and E. K. Molloy, "Psychological safety in feedback: What does it look like and how can educators work with learners to foster it?," *Med. Educ.*, vol. 54, no. 6, pp. 559–570, 2020, doi: 10.1111/medu.14154.

[33] S. Han, D. Liu, and Y. Lv, "The Influence of Psychological Safety on Students' Creativity in Project-Based Learning: The Mediating Role of Psychological Empowerment," *Front. Psychol.*, vol. 13, 2022, Accessed: Nov. 01, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.865123

[34] C. Andriopoulos, "Determinants of organisational creativity: a literature review," *Manag. Decis.*, vol. 39, no. 10, pp. 834–841, Jan. 2001, doi: 10.1108/00251740110402328.

[35] E. M. L. S. De Alencar and M. F. De Bruno-Faria, "Characteristics of on Organizational

Environment which Stimulate and Inhibit Creativity*," *J. Creat. Behav.*, vol. 31, no. 4, pp. 271–281, 1997, doi: 10.1002/j.2162-6057.1997.tb00799.x.
[36] E. P. Douglas, S. Agdas, C. Lee, M. Koro-Ljungberg, and D. J. Therriault, "Ambiguity during engineering problem solving," in *2015 IEEE Frontiers in Education Conference (FIE)*, Oct. 2015, pp. 1–4. doi: 10.1109/FIE.2015.7344305.
[37] E. P. Douglas, M. Koro-Ljungberg, N. J. McNeill, Z. T. Malcolm, and D. J. Therriault, "Moving beyond formulas and fixations: solving open-ended engineering problems," *Eur. J. Eng. Educ.*, vol. 37, no. 6, pp. 627–651, Dec. 2012, doi: 10.1080/03043797.2012.738358.
[38] N. J. Mourtos, N. D. Okamoto, and J. Rhee, "Open-Ended Problem-Solving Skills in Thermal Fluids Engineering," *Glob. J. Eng. Educ.*, vol. 8, no. 2, 2004.
[39] F. G. Splitt, "The Challenge to Change: On Realizing the New Paradigm for Engineering Education," *J. Eng. Educ.*, vol. 92, no. 2, pp. 181–187, 2003, doi: 10.1002/j.2168-9830.2003.tb00756.x.
[40] J. Walther and D. F. Radcliffe, "The competence dilemma in engineering education: Moving beyond simple graduate attribute mapping," *Australas. J. Eng. Educ.*, vol. 13, no. 1, pp. 41–51, Jan. 2007, doi: 10.1080/22054952.2007.11464000.
[41] L. R. Lattuca, P. T. Terenzini, and B. J. Harper, "2020 Vision: Progress in Preparing the Engineer of the Future," Ann Arbor, MI, 2014.
[42] R. P. Loweth, S. R. Daly, L. Paborsky, S. L. Hoffman, and S. J. Skerlos, "'You Could Take "Social" Out of Engineering and Be Just Fine': An Exploration of Engineering Students' Beliefs About the Social Aspects of Engineering Work," presented at the 2021 ASEE Virtual Annual Conference Content Access, Jul. 2021. Accessed: Feb. 15, 2023. [Online]. Available: https://peer.asee.org/you-could-take-social-out-of-engineering-and-be-just-fine-an-exploration-of-engineering-students-beliefs-about-the-social-aspects-of-engineering-work
[43] B. Lutz and M. C. Paretti, "Exploring the Social and Cultural Dimensions of Learning for Recent Engineering Graduates during the School-to-Work Transition," *Eng. Stud.*, vol. 13, no. 2, pp. 132–157, May 2021, doi: 10.1080/19378629.2021.1957901.
[44] K. H. Sienko *et al.*, "Global Health Design: Clinical Immersion, Opportunity Identification and Definition, and Design Experiences," *Int. J. Eng. Educ.*, vol. 34, no. 2(B), pp. 780–800, 2018.
[45] J. Schneider, J. A. Leydens, and J. Lucena, "Where is 'Community'?: Engineering education and sustainable community development," *Eur. J. Eng. Educ.*, vol. 33, no. 3, pp. 307–319, Jun. 2008, doi: 10.1080/03043790802088640.