The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
ASEE
Paper ID #42689

Ill-Structured Design Challenges in First-Year Courses

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Abstract

In this Complete Research Paper, we investigate how first-year students in two departments (Chemical and Biological Engineering and Civil, Construction, and Environmental Engineering) navigate the same sociotechnical design challenge based on the Gold King Mine spill and the problem of acid mine drainage. We found that students in these two departments not only thought about the problem differently between teams but between departments. We also found that students took agency over the experiences of stakeholders as they considered stakeholder needs, and identified community outreach and community resources as key constraints on their final designs.

Introduction and research purpose

Design challenges are difficult for students because of the nature of these problems. They are ill-structured [1], meaning there are many possible satisfactory solutions, as well as many possible paths toward a solution, requiring designers to frame the problem by deciding what to focus on about the problem. This aspect also makes teaching design difficult, especially in the first year when students have completed little to none of their technical coursework. To overcome this issue, faculty sometimes reduce the complexity by making the design problem purely technical, removing social and policy factors. However, this approach can actually make the problem more difficult for students, by obscuring the problem context and meaning. Another way faculty address the issue is by reducing the ill-structuredness, providing kit-based projects in which students lack opportunities to frame the problem.

We sought to investigate how first-year students navigated a complex and ill-structured design challenge, guided by the research questions:

- To what extent do CBE and CCEE first-year engineering students frame an ill-structured design challenge differently?
- In what ways do first-year engineering students consider stakeholders' perspectives during framing?
- To what extent do first-year engineering students view the design challenge as constrained?

Background

How do design problems differ from other kinds of problems?

Problems students solve in instructional settings are typically *complex* - they have a large number of variables that are interrelated and must be managed to successfully find a solution. However, a majority of problems in instructional settings, including in engineering are also *well structured* which means that there is one correct answer to the problem and one correct method to achieve that answer [2]. In contrast, design problems are *ill-structured* [1]. These problems do not have single right answers because they must be framed before they can be solved [3]. Framing involves making decisions about what part of the problem is important, who the stakeholders might be, and what the attributes of a successful solution are [4]. Because these decisions are unique to each designer, solutions to ill-structured problems are also unique. Design problems are iterative rather than a linear progression from problem to solution. Designers must go back and reevaluate the problem and the potential solutions during the design process [5]. This relationship between problem and solution results in a complex process where designers may go back and change the problem part way through solving the problem [6].

Why might situated and sociotechnical problems support learning?

Design problems are inherently sociotechnical [7], meaning the technical factors are related to and depend upon social factors [8]. These types of problems include considerations about stakeholders, cultural inequality, and environmental impacts and are situated in that they are embedded into their context. These types of problems focus particularly on the social and material context of the problem [9], [10] and reject the idea that technical considerations of a problem can be removed from the impacts and influences of the design.

Often, engineering problems are treated as only technical, with a focus on optimizing elements like time or money. However, these solutions may not be effective in real situations, where influences like stakeholder issues or ethics concerns can make a technically optimized problem useless. In addition, instructors who fear overwhelming students (particularly first year students) or having problems that are too difficult to tackle often remove the context [11]. However, situated problems support students to contextualize their place within the learning environment [12] as well as the larger community [13], which in turn supports their identity development [9]. This is particularly important for minoritized students who can better identify with being an engineering professional [14].

How do students learn engineering design?

Expert or experienced designers engage in behaviors unique to design problems. They gather information to understand the problem through multiple channels [15] including clarifying ambiguity and determining solutions that have been tried by others [16]. Designers in turn assess constraints, including stakeholder needs, design requirements, gaps in knowledge, and available resources [16].

Because novice engineers rarely have opportunities to engage in design problems in their prior education, these skills need to be developed. When faced with design problems, more experienced senior designers considered more factors (from different topic areas), and those factors were considered more deeply than their novice counterparts. Senior designers made decisions systematically about what factors needed to be scoped than freshmen designers who tended to stay within the narrow range of their first conceptualizations [17]. Both less and more experienced engineers learning design consider the ways that the context impacts successful solutions [18] however more experienced engineering students iterated and revised their solutions to a greater extent during the process [19].

A key to the process of learning design, as with other difficult subjects, is supported by *scaffolding*, the instructional method that provides guidance and support to students as they learn, with the intention of removing the scaffolds when students become skilled, just as when a building's scaffolding is removed after construction is complete [20]. In engineering design, scaffolding can range from prescribed steps to artificial constraints to simplify the problem [21] and help students still learning to better build their knowledge and skills. Students can use these supports to build their core competencies and have a better understanding of the design process when given opportunities to design in ways that allow for slowly building skills [22]. However, retaining these supports at the same level as students gain skills doesn't allow for further progression [23].

How does constraint impact engineering design?

Constraint is an endemic attribute of design problems [24] because design problems do not happen in a vacuum. Constraint often comes from the context, and identifying constraints is part of the initial framing process. Design problems are not completely constrained, however (as this would make them well-structured problems). In educational settings, it is tempting when developing a design challenge that is very constrained as a way to support students to be successful, however, this fails to teach design skills [25]. On the other hand, design projects that have no constraints at all are not authentic and contextless [26].

When learning design, engineering students have to make decisions about what constraints to focus on, which to accept, and which ones to disregard [25]. Not all theoretical constraints need to be obeyed as part of a design [26]. Those decisions about constraint are reevaluated over the course of the design, with constraints being refined as the designers learn more [27].

Methodology

Study design, setting, and participants

To conduct the study we engaged in design-based research, which instantiates learning theory in the instruction and tests it iteratively in the classroom [28]. We conducted the study in two introductory courses at an R1 university in the southwestern US: a 3-credit Civil, Construction, and Environmental Engineering course (CCEE, n = 81) and a 1-credit Chemical and Biological Engineering course (CBE, n = 49). Teams comprised 3 to 4 students (CCEE, n = 24 teams; CBE, n = 19 teams).

We developed an ill-structured design challenge centered around the Gold King Mine spill in 2015. This disaster released pollution into waterways across the southwest, including water sources that rural communities need to survive. We asked students to identify a community in our state that would be impacted by a mine drainage spill and design a water remediation solution for that specific community, including community engagement to encourage adoption of their solution. They tested their solutions in a simulation before moving to a bench-scale test. Scaffolded deliverables guided them on identifying the problem, researching current solutions, and drawing conclusions from their data. The final deliverable was a short presentation where teams communicated the community they chose, including population and water requirements, their proposed solution, the data used to justify that solution, and their plan for community engagement.

Data collection and analysis

Data were collected following institutional review board approval of our study protocol and informed consent was collected from students. We collected team deliverables as well as distributed a survey at the end of the design challenge intended to understand the agency students experienced during the challenge [29], [30].

To understand how students framed the problem of acid mine drainage, we inductively coded the potential solutions to acid mine drainage proposed during the ideation phase deliverable of the challenge [31]. Table 1 shows the categories and examples within those categories. We conducted a chi square test of difference to determine if the number of suggestions varied across the two departments. Chi squared tests are used to determine the significant difference of categorical data, compared to t tests that are used for continuous data. Chi squared tests, like t tests, are tested against a critical value, resulting in a p value that can be assessed for significance [32].

Table 1: Categories of potential solutions to acid mine drainage proposed by teams

Solution Type	Examples
pH remediation	Limestone trenches, soda ash
Physical filtration	Nanofiltration, riverbank filtration
Heavy metal capture	Activated carbon, sludge precipitation, ion exchange
Bacteria	Sulfate bacteria
Physical mine management	Mine capping, mine filling
Treatment plants	Wastewater, sewage

To interrogate the ways teams agentivity take up stakeholder perspectives, we explored the deliverable task that asked teams to describe the feelings and needs of three stakeholders: community members, farmers, and government employees. We take a discourse analysis approach, with particular focus on the subject and verb types in verbal clauses. In this way, “I” denotes individual agency;“we” denotes shared; third-person subjects denote attributed agency; modal verbs such as “going to” and “could”denote tentativeness characteristic of framing agency; and modal verbs such as “can’t” and “have to” denote offloading of agency [33].

We analyzed the survey construct of constraint [30] through a one-tailed t-test to explore the variance between the two departments.

Results

Framing the problem: Disciplinary influences

The first deliverable of the challenge asked students to choose and research three potential remediation methods for acid mine drainage. Teams had to make decisions about what types of remediation were available and what was being remediated. This includes raising the pH of the acidic water and removing heavy metals as well as considerations about whether to treat the issue at the source (the mine), in the river itself, or when it is removed from the river to be used. Table 1 shows the number of solutions proposed of each type. Because each team proposed three solutions, the total number of possible solutions is greater than the number of teams. CBE students were significantly more likely to propose chemical pH remediation solutions, $\chi^2(1, N = 2) = 4.01$, $p = 0.045$. CCEE students were significantly more likely to propose heavy metal capture solutions, $\chi^2(1, N = 2) = 5.24$, $p = 0.022$. The difference between other categories did not vary across departments.

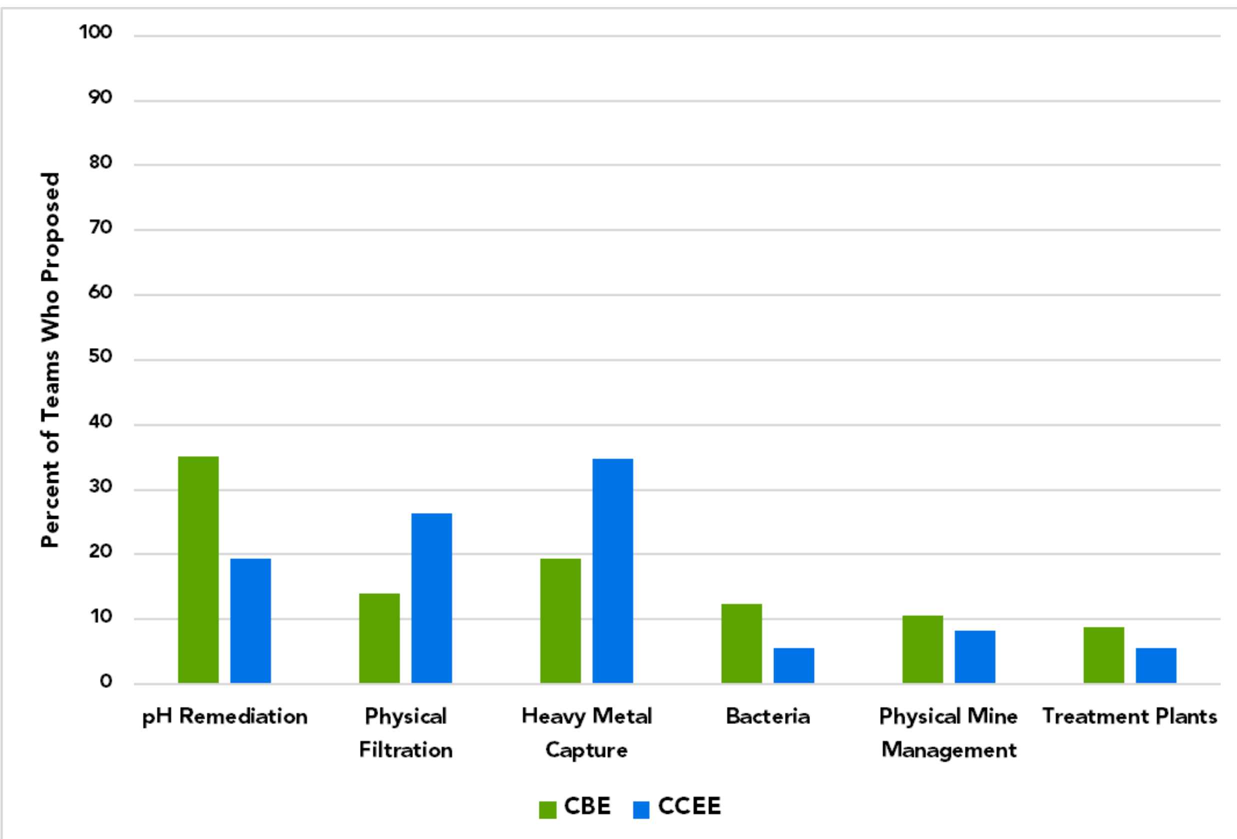

Figure 1: Comparison of percent of teams across courses (CBE and CCEE) that proposed acid mine drainage remediation solutions in categories of chemical pH neutralization, physical filtration, heavy metal capture, physical mine management, and treatment plants

Thus, these findings suggest a disciplinary influence on how students framed the problems. A statistically significantly greater number of CBE students framed the problem to consider how to increase the pH, while a significantly greater number of CCEE students framed the problem to focus on heavy metal removal. This suggests that teams framed the problem in ways reflecting aspects of their disciplines. Teams could make consequential choices about the ways that they wanted to approach the problem, even in the exploratory phase of the problem.

While other types of considerations didn't differ between courses, the range of ways that students conceptualized the problem is large. Some teams considered physically stopping up the mine, while others suggested longer-term industrial facilities. In the first, the problem is considered to be drainage that was still coming out or could come out of the mine. In the second, the problem is considered to be fixing the drainage that is already in communities. There are both reasonable but distinct ways to approach acid mine drainage. Teams also at this early stage in the design process remained tentative, exploring several types of ideas. No team in either course suggested three ideas in the same category of solutions. Instead, they thought about multiple ways to think about the problem.

Subsequent to exploring possible remediation, teams identified target communities to target for remediation designs. The only stipulations were that their communities needed to be in the state and had to have been affected by acid mine drainage or could be affected in the future, including those that could come into contact with contaminated water downstream. Table 2 shows the types of locations teams chose.

Table 2: Locations of communities chosen by teams

	CBE	CCEE
Urban	1	0
Rural	8	12
Unincorporated	5	7
Sovereign Tribal Land	5	5
Total	19	24

While none of the differences between the courses in terms of the communities that the teams chose are statistically significant, this demonstrates the range of ways that the students chose to conceptualize the people that acid mine drainage can impact. Some locations, particularly unincorporated areas, are filled mostly with ranches where the greatest impacts are to cattle. Some rural towns are geared to the mine in their area, others are tourist destinations, all of which require different solutions. These choices require different assessments about the communities most impacted, including whether livestock should be considered, or if communities with access to multiple sources of water should be considered.

Identifying contextual constraints on solutions

During the problem-framing process, students were asked to consider the needs and feelings of different stakeholders of an acid mine disaster: community members, farmers, and government agencies. This deliverable scaffolded teams to situate their designs in the needs and wants of the stakeholders of the region. Figure 1 shows the response from one CBE team.

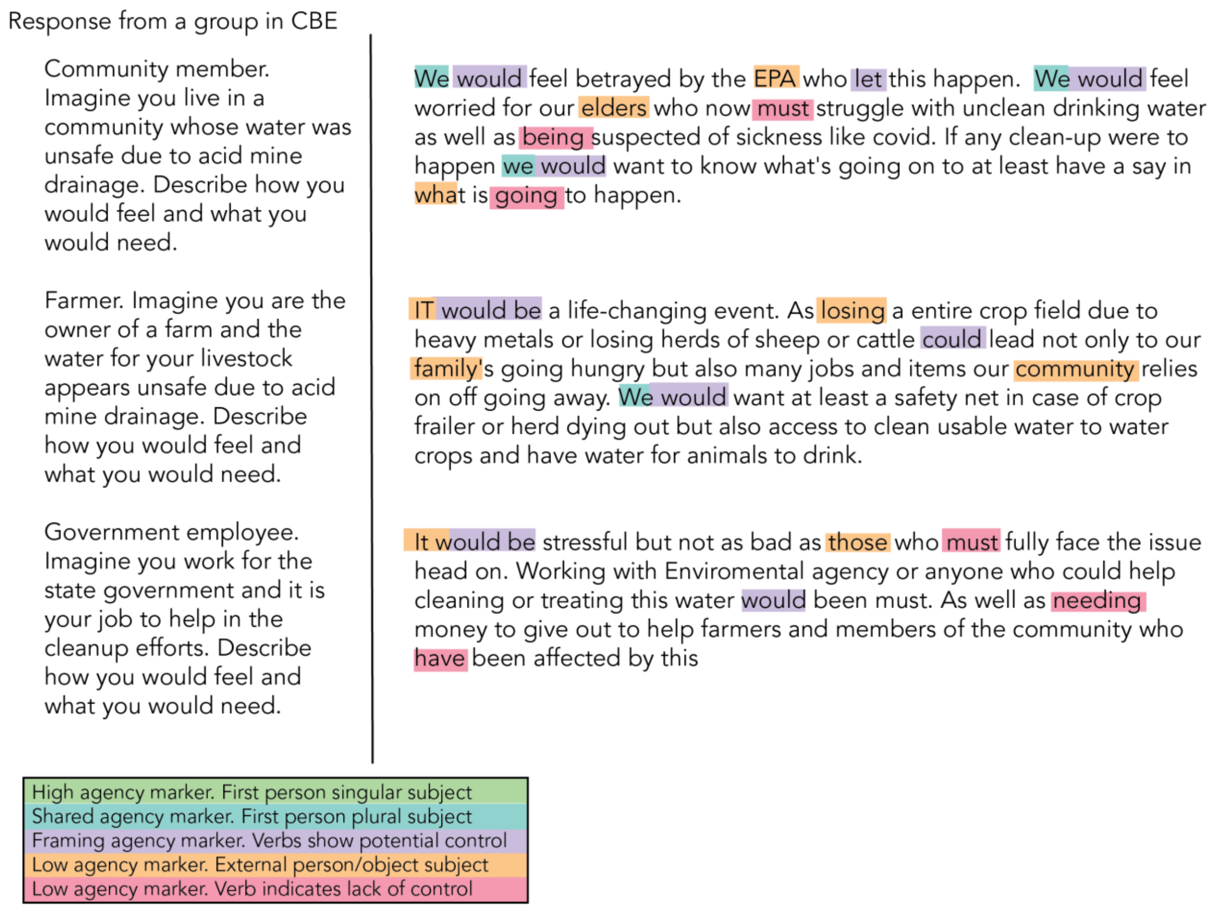

Figure 1: CBE team when asked to identify experiences and needs of different communities.

This team framed their ideas about community needs through collective pronouns, qualifying many third-person nouns as “our.” They remained tentative bout feelings and actions but showed low agency when talking about what had happened. Figure 2 shows a corollary response from a team in CCEE.

Response from a group in CCEE

Community member. Imagine you live in a community whose water was unsafe due to acid mine drainage. Describe how you would feel and what you would need.	- I would feel extremely worried as I wouldn't know if the water I use everyday (sinks, shower, washing machine, fridge) would be safe to use - I would need water that is safe to drink, so water bottles would be the safest option - I would need to know when the water would become safe to use - Stay away from the contaminated river
Farmer. Imagine you are the owner of a farm and the water for your livestock appears unsafe due to acid mine drainage. Describe how you would feel and what you would need.	- I would be devastated because I would not be able to give the livestock water which they need to live - I'd have to find a quick solution to try and find clean water for the livestock so they don't die, the - I'd like for authorities to get involved as fast as possible and I would also like to seek compensation for the damage it causes to the farm
Government employee. Imagine you work for the state government and it is your job to help in the cleanup efforts. Describe how you would feel and what you would need.	- They would make sure that word gets out to not drink or use most of the water from several places - They would hire engineers to come up with a solution on how to fix the water, which is a process that could take a large amount of time - There would need to be ways to get clean water back to the people whether it be water bottles, filtration devices and the expense of the government and state for causing the problem in the first place

High agency marker. First person singular subject
Shared agency marker. First person plural subject
Framing agency marker. Verbs show potential control
Low agency marker. External person/object subject
Low agency marker. Verb indicates lack of control

Figure 2: CCEE team when asked to identify experiences and needs of different communities.

Broadly, we see that teams show high agency in the imagined feelings of community members and farmers and lower agency over the events that lead to those feelings. Students are conceptualizing the problem as one where the disaster has happened, rather than a problem that can be prevented but that the feelings that the disaster has brought up are more agentive. In addition, teams identified personally with community members and farmers (using I or we) and impersonally with governmental agents (using they). This indicates that the experiences of the people directly impacted by acid mine drainage are kept more closely in mind when considering the constraints.

In the survey at the end of the design challenge, students were asked to report the extent to which they felt that the design was constrained, with a 1 indicating no constraint, and 7 indicating completely constrained. Students reported that the design challenge was somewhat constrained (CCEE: $M = 5.05$, $SD = 1.33$; CBE $M = 5.27$, $SD = 1.56$.) The difference between departments was not statistically significant ($t(105)=0.7621$, $p = 0.45$.) However, students on average identified the problem as constrained.

When asked in a free response, "Design problems often have constraints, such as budget limitations, material properties, performance requirements, and other requirements set by the stakeholders and situations in which the design solution will be used. What are some constraints on the design problem you are working on?" Students identified both academic constraints such as the amount of time allotted to the project and materials available to test prototypes in the lab, as well as contextual constraints such as community involvement and resources available to the community. Of the respondents, we found that a majority of them identified contextual constraints (CBE = 72%; CCEE = 68%) while a substantial number identified course-based constraints (CBE = 42%, CCEE = 49%). While constraints placed on students as a function of being in a classroom setting played a role in the design process, the sociotechnical considerations brought out by the context also played a role.

Overall we found students leveraged the sociotechnical nature to navigate the ill-structured challenge and framed the problems differently not just between teams, but between courses.

Conclusions

- To what extent do CBE and CCEE first-year engineering students frame an ill-structured design challenge differently?
- In what ways do first-year engineering students consider stakeholders' perspectives during framing?
- To what extent do first-year engineering students view the design challenge as constrained?

In looking to understand how first-year students framed and explored a complex and ill-structured problem, we found that while both CBE and CCEE students framed the problem in somewhat different ways, they were able to consider different angles to look at the issue, consider stakeholders, and identify constraints. Students took a variety of perspectives about what the problem might be, leading them to suggest different solutions during the ideation phase of the design challenge, which to some extent was explained by whether the teams were in chemical or civil engineering. We also found that teams took up the perspectives of the stakeholders of their chosen communities in agentive and empathetic ways, considering these perspectives as part of the constraints they considered while designing.

This work has implications for other first-year engineering courses looking to implement design challenges. Despite prevalent concerns that first-year students would struggle when faced with complex problems they have to agentively solve, this shows that these students can successfully do design work to frame and conceptualize large and difficult problems.

There are several limitations to this work. The primary limitation lies in the differing number of credit hours between the two courses. This is reflected in students in the CCEE course having more accurate calculations when analyzing their data collected in the lab, and having more professional presentation slides. However, these results show that even a 1-credit class allows for nuanced design work from first-year engineers. The sample size for this study is also relatively small, limiting universalizing due to small-scale statistics.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Grant No. 1751369 and No. 1914490 as well as The UNM School of Engineering Teaching Innovation Fellows Award. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

[1] D. H. Jonassen, "Toward a Design Theory of Problem Solving," *Educ. Technol. Res. Dev.*, vol. 48, no. 4, pp. 63–85, 2000, doi: https://doi.org/10.1007/BF02300500.
[2] H. A. Simon, "The structure of ill structured problems," *Artif. Intell.*, vol. 4, no. 3, pp. 181–201, Dec. 1973, doi: 10.1016/0004-3702(73)90011-8.
[3] K. Dorst, "On the problem of design problems - problem solving and design expertise," *Journal of Design Research*, vol. 4, no. 2. pp. 185–196, Jan. 2004. doi: 10.1504/JDR.2004.009841.
[4] D. A. Schön, "Problems, frames and perspectives on designing," *Des. Stud.*, vol. 5, no. 3, pp. 132–136, Jul. 1984, doi: 10.1016/0142-694X(84)90002-4.
[5] J. W. Getzels, "Problem finding: A theoretical note," *Cogn. Sci.*, vol. 3, no. 2, pp. 167–172, 1979, doi: 10.1207/s15516709cog0302_4.
[6] K. Dorst and N. Cross, "Creativity in the design process: co-evolution of problem–solution," *Design Studies*, vol. 22, no. 5. pp. 425–437, Sep. 01, 2001. doi: 10.1016/S0142-694X(01)00009-6.
[7] L. J. Ball, B. Onarheim, and B. T. Christensen, "Design requirements, epistemic uncertainty and solution development strategies in software design," *Des. Stud.*, vol. 31, no. 6, pp. 567–589, Nov. 2010, doi: 10.1016/j.destud.2010.09.003.
[8] A. Cherns, "The Principles of Sociotechnical Design," *Hum. Relat.*, vol. 29, no. 8, pp. 783–792, Aug. 1976, doi: 10.1177/001872677602900806.
[9] A. Johri and B. M. Olds, "Situated Engineering Learning: Bridging Engineering Education Research and the Learning Sciences," *J. Eng. Educ.*, vol. 100, no. 1, pp. 151–185, 2011, doi: 10.1002/j.2168-9830.2011.tb00007.x.
[10] M. Koretsky, C. Kelly, and E. Gummer, "Student Perceptions of Learning in the Laboratory: Comparison of Industrially Situated Virtual Laboratories to Capstone Physical Laboratories," *J. Eng. Educ.*, vol. 100, no. 3, pp. 540–573, 2011, doi: 10.1002/j.2168-9830.2011.tb00026.x.
[11] F. M. Kamaruzaman, R. Hamid, and A. A. Mutalib, "A review on issues and challenges in incorporating complex engineering problems in engineering curriculum and proposed solutions," in *2017 7th World Engineering Education Forum (WEEF)*, Nov. 2017, pp. 697–701. doi: 10.1109/WEEF.2017.8467167.
[12] T. D. Sadler, "Situated learning in science education: socio-scientific issues as contexts for practice," *Stud. Sci. Educ.*, vol. 45, no. 1, pp. 1–42, Mar. 2009, doi: 10.1080/03057260802681839.
[13] J. Lave and E. Wenger, *Situated learning: Legitimate peripheral participation*. in Situated learning: Legitimate peripheral participation. New York, NY, US: Cambridge University Press, 1991, p. 138. doi: 10.1017/CBO9780511815355.
[14] D. Hamman-Fisher and V. McGhie, "Towards decoloniality of the education training and development third-year curriculum: Employing situated learning characteristics to facilitate authentic learning," *Cogent Educ.*, vol. 10, no. 2, p. 2237301, Dec. 2023, doi: 10.1080/2331186X.2023.2237301.
[15] K. M. Bursic and C. J. Atman, "Information Gathering: A Critical Step for Quality in the Design Process," *Qual. Manag. J.*, vol. 4, no. 4, pp. 60–75, Jan. 1997, doi:

10.1080/10686967.1998.11919148.
[16] M. Basadur, G. B. Graen, and S. G. Green, “Training in creative problem solving: Effects on ideation and problem finding and solving in an industrial research organization,” *Organ. Behav. Hum. Perform.*, vol. 30, no. 1, pp. 41–70, Aug. 1982, doi: 10.1016/0030-5073(82)90233-1.
[17] A. Morozov, D. Kilgore, and C. Atman, “Breadth In Design Problem Scoping: Using Insights From Experts To Investigate Student Processes,” presented at the 2007 Annual Conference & Exposition, Jun. 2007, p. 12.321.1-12.321.24. Accessed: Dec. 13, 2022. [Online]. Available: https://peer.asee.org/breadth-in-design-problem-scoping-using-insights-from-experts-to-investigate-student-processes
[18] L. J. Ball, L. Maskill, and T. C. Ormerod, “Satisficing in engineering design: causes, consequences and implications for design support,” *Autom. Constr.*, vol. 7, no. 2, pp. 213–227, Jan. 1998, doi: 10.1016/S0926-5805(97)00055-1.
[19] C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey, and L. J. Leifer, “Engineering Design Thinking, Teaching, and Learning,” *J. Eng. Educ.*, vol. 94, no. 1, pp. 103–120, 2005, doi: https://doi.org/10.1002/j.2168-9830.2005.tb00832.x.
[20] B. J. Reiser, “Scaffolding Complex Learning: The Mechanisms of Structuring and Problematizing Student Work,” *J. Learn. Sci.*, vol. 13, no. 3, pp. 273–304, Jul. 2004, doi: 10.1207/s15327809jls1303_2.
[21] J. N. Phanthanousy, C. A. Whitfield, and Y. S. Allam, “Scaffolding Provided to Engineering Students in Cornerstone Design Project Scenarios Related to Practices of Expert Designers,” presented at the 2012 ASEE Annual Conference & Exposition, Jun. 2012, p. 25.1141.1-25.1141.15. Accessed: Feb. 08, 2024. [Online]. Available: https://peer.asee.org/scaffolding-provided-to-engineering-students-in-cornerstone-design-project-scenarios-related-to-practices-of-expert-designers
[22] N. Phanthanousy and Y. Allam, “First-year / senior year design data: Preliminary results from ongoing research on post-secondary design student activities,” in *2013 IEEE Frontiers in Education Conference (FIE)*, Oct. 2013, pp. 1118–1120. doi: 10.1109/FIE.2013.6685003.
[23] A. J. Dutson, R. H. Todd, S. P. Magleby, and C. D. Sorensen, “A review of literature on teaching engineering design through project-oriented Capstone courses,” *J. Eng. Educ.*, vol. 86, no. 1, pp. 17–28, 1997, doi: 10.1002/j.2168-9830.1997.tb00260.x.
[24] M. D. Gross, S. M. Ervin, J. A. Anderson, and A. Fleisher, “Constraints: Knowledge representation in design,” *Des. Stud.*, vol. 9, no. 3, pp. 133–143, Jul. 1988, doi: 10.1016/0142-694X(88)90042-7.
[25] E. Meir, D. Pope, J. K. Abraham, K. J. Kim, S. Maruca, and J. Palacio, “Designing Activities to Teach Higher-Order Skills: How Feedback and Constraint Affect Learning of Experimental Design,” *CBE—Life Sci. Educ.*, vol. 23, no. 1, p. ar1, Mar. 2024, doi: 10.1187/cbe.22-08-0158.
[26] M. M. Dabbeeru and A. Mukerjee, “Discovering implicit constraints in design,” *AI EDAM*, vol. 25, no. 1, pp. 57–75, Feb. 2011, doi: 10.1017/S0890060410000478.
[27] C. M. Burns and K. J. Vicente, “A participant-observer study of ergonomics in engineering design:: how constraints drive design process,” *Appl. Ergon.*, vol. 31, no. 1, pp. 73–82, Jan. 2000, doi: 10.1016/S0003-6870(99)00017-4.
[28] The Design-Based Research Collective, “Design-Based Research: An Emerging Paradigm for Educational Inquiry,” Educational Researcher, vol. 32, no. 1, pp. 5–8, Jan. 2003, doi:

10.3102/0013189X032001005.
[29] V. Svihla, A. Gallup, and S. “Pil” Kang, “Development and Insights from the Measure of Framing Agency,” presented at the 2020 ASEE Virtual Annual Conference Content Access, Jun. 2020. Accessed: Jul. 05, 2021. [Online]. Available: https://peer.asee.org/development-and-insights-from-the-measure-of-framing-agency
[30] M. Wilson-Fetrow, V. Svihla, and A. Olewnik, “Confirmatory factor analysis of the framing agency survey,” presented at the 2023 ASEE Annual Conference & Exposition, Jun. 2023. Accessed: Feb. 08, 2024. [Online]. Available: https://peer.asee.org/confirmatory-factor-analysis-of-the-framing-agency-survey
[31] J. Saldaña, “The coding manual for qualitative researchers.” Sage, 2009.
[32] R. L. Plackett, “Karl Pearson and the Chi-Squared Test,” *International Statistical Review / Revue Internationale de Statistique*, vol. 51, no. 1, pp. 59–72, 1983, doi: 10.2307/1402731.
[33] V. Svihla, T. B. Peele-Eady, and A. Gallup, “Exploring agency in capstone design problem framing,” *Studies in engineering education*, vol. 2, no. 2, Jan. 2021, doi: 10.21061/see.69.