Framing Engineering Problems in an Intramural Context

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Abstract
Supporting students to frame design problems is one of the most challenging aspects of engineering education, and as faculty, sharing agency with students, such that they have framing agency to make decisions that are consequential to the problem frame is difficult. In this paper, we report on students' progress framing authentic problems early and after four months of work. Set in a high-agency, co-curricular intramural program where students work on interdisciplinary design projects, we found, using surveys and student work, that early in the process, students reported open-ended problems constrained somewhat by budget or design requirements. Over time, they came to recognize their own limitations as constraining, became more tentative in their treatment of the problem, and reported opportunities to learn from their own and peers' decisions. Students who reported opportunities to learn also reported working on somewhat more constrained problems yet being able to make consequential decisions. Collectively, this suggests problems that offer a Goldilocks middle ground, that include endemic constraints yet allow students to make consequential decisions may be a key ingredient for developing problem framing capacity. We share instructional implications related to supporting students to differentiate between design requirements and constraints, in shifting from qualitative understandings to quantitative requirements and their role in doing so, and navigating their own limitations.

Introduction & research purpose

Students often don't recognize the need to frame ill-structured problems because they have abundant experience with well-structured problems. Even if they understand the need to do so, existing tools lack sufficient scaffolding to help students decide when and how to use tools to frame problems. To deal with this, many instructors make using such tools into course assignments, but this can lead students to view them as busy work, rather than seeing them as powerful tools that serve specific purposes.

In this study, we investigated how students in an intramural program learned to direct their problem framing process. We examined the degree to which they exhibited framing agency—making decisions consequential to their framing of the problem—near the beginning of their problem framing and after four months of work.

Framework

We situate our study with research and theory that characterize much of engineering design practice as framing ill-structured problems, which in turn brings our focus to decision making—or agency. We build on recent work that examines agency in engineering education [1] and its salience for student learning and development. We consider the implications of these for experiential learning settings, such as first-year and capstone design, and intramural experiences.

Jonassen [2] proposed a typology to characterize problems according to their complexity—the number of variable or factors in a problem and the degree to which these are interconnected; their domain specificity—the degree to which deep disciplinary knowledge and practices are needed to solve a problem; and their structure—presented as a continuum from well-structured problems that have a single, correct solution and most efficient solution path to ill-structured

problems that have many satisficing solutions and solution paths. Many have leveraged this simple and general framework to characterize both the practice and educational experiences of engineers, including more deliberately situating engineering problem types that involve problem framing [3]. These efforts have clarified that engineering design problems and engineering case analyses both present ill-structured problems, which engineers must frame before reaching a solution. What engineers do in framing problems and the decisions they make as they do so has dramatic implications for the effectiveness and creativity of their solutions [4, 5]. In this way, engineering designers, even when working for a client, have significant agency [6-8] which they use to make decisions that are consequential to their framing of the problem [9, 10].

In social and learning sciences, agency has typically been studied as decision-making constrained by structures [11]. These structures have been cast as impervious [12] or resiliently reproduced [13]. Such characterizations suggest that even when a problem is considered ill-structured, there are still structures present that prevent certain decisions. We might cast these as design constraints or requirements, such as budgetary considerations and material regulations that govern decisions (e.g., those that relate to biocompatibility). We might also cast these as forms of design fixation, as the reproduction of flaws or elements that prevent a solution from solving a problem in a novel manner. And in engineering classrooms, these structures can also include students' expectations about teaching and learning and their perceptions of problems as solvable using sequential and teleological methods [14].

Scholars have argued that a central purpose of higher education should be expanding students' agency [15]. Yet, it is clear that this is a tension within engineering programs [16, 17], because much of students' past educational experiences and typical core engineering coursework emphasize solving well-structured problems [18, 19]. Recent research has begun to build consensus that higher agency learning experiences are particularly beneficial for students from groups that are underrepresented in engineering [20, 21]. This line of work emphasizes student agency as instrumental to overcoming structural oppression [22] and as appealing to students who have justice-oriented goals [23].

In response to these results, we see more clearly the potential value of learning experiences that encourage students to use their agency to make decisions that are consequential to problem frames. Termed *framing agency*, this construct aims to bring attention to the kinds of learning experiences that students need in order to develop their capacity to direct framing and reframing of design problems. For instance, while first-year design projects are increasingly common, not all projects are ill-structured enough to allow for problem framing; instructors may introduce too many constraints as a means to make grading feasible [24]. Alternatively, when problems are under-constrained, students may flounder amidst too many decisions [25, 26]. And, even when design projects are ill-structured, students may not recognize their roles in framing problems. Thus, understanding more about students' responses to a range or realistic design challenges can inform engineering education researchers and practitioners on ways to provide increased opportunities for students to develop problem framing capacity.

Methodology
We investigated how students perceived engineering projects as part of an intramural experience. Using a pre/post design, we sought to answer the following research questions:

- Early in their problem framing work, how do students in an intramural program perceive constraints, problem structure, and their roles in framing engineering problems?
- How does this change as students are supported to frame and plan ways to solve engineering problems?

Setting and participants

Engineering Intramurals is a co-curricular project-based learning program. The program brings together students from multiple departments to solve problems sourced from industry, community groups, and academic competitions. The instructor met with sponsors to ensure they understand the purpose and pace of the project as a learning experience.

Projects come from a variety of domains and can vary significantly in their initial goals. For example, one project, sponsored by the university's Sustainability Office asked students to investigate the use of road salt on campus during the winter months to better understand its impacts on the campus' built and natural environment. The project is motivated by perceptions that there may be opportunity to reduce salt use on campus. Another project points students to a small, windowed hallway space near the undergraduate education office and asks them to design a greenhouse that integrates automation. The sponsor is the experiential learning program but there is no specific use-case imagined; that decision has been left up to the student team. A third project asks students to design a user interface for a soccer score keeping software application. The project sponsor has an existing application for hockey and wants to develop a similar product for other sports, like soccer, which requires consideration of the scorekeeping tasks for each sport.

The project occurs in three phases across the academic year. The first phase focuses on problem elaboration and framing (fall semester), followed by project planning (winter), and concluding with solution realization (spring). To support students to learn to frame problems, the instructor situates the project as developing professional competencies, sets expectations that the entire semester is focused on framing, and supports students to critically evaluate engineering methods.

We see the intramural context as an ideal setting to study the development of framing agency because of the volitional nature of co-curricular experiences. As a high agency setting, students have many forms of agency available to them, from decisions about whether to participate and how much effort to invest, to whether to prioritize components of the experience as other requisite deadlines loom. Intersecting with this, they make decisions about their interactions as a team, with their client, and about the problem frame.

Data collection and analysis

Students completed the same survey a few weeks into the first problem framing phase, and after completing their project planning phase. The core framing agency survey was developed following standard procedures [27, 28], including work to evaluate the validity of data the survey provides for research and teaching purposes [9]. The framing agency survey includes 18 7-point Likert-scaled items, plus three contextualizing constructed response items (Table 1). These contextualizing questions ask students to describe specific constraints encountered, decisions made personally, and decisions made by someone else in the team; students then answer Likert-scaled items about their perceptions of these.

We added additional constructed response items to better understand students' framing of problems over time.

- What do you know about the problem? How are you sure you know?
- What do you wonder about the problem? From whose point of view might the problem be different?
- How will you learn more about this aspect of the problem? How will you know you have enough information?

Table 1. Framing agency survey items organized by latent factor.

Factor: Individual Consequentiality
How responsible or not responsible have you felt for the outcomes of the project?
Considering the decision you described, how important or unimportant was the decision?
Considering the decision you described, how important or unimportant was the impact of that decision on your process?
How responsible or not responsible have you felt for making decisions personally?
How responsible or not responsible have you felt for coming up with your own ways to make progress on the project?
Factor: Shared Consequentiality
Considering the decision you described, how important or unimportant was the decision?
Considering the decision you described, how important or unimportant was the impact of that decision on your process?
Factor: Learning as Consequentiality
How much or little have you learned as a result of decisions about the problem you personally made?
How much or little have you learned as a result of decisions about the problem a teammate made?
Factor: Constrainedness
Considering these constraints, how free or restricted have you felt when making decisions yourself?
Considering these constraints, how free or restricted have your teammates seemed when making decisions?
How free or limiting does the problem seem to be?
Factor: Shared tentativeness / Ill-structuredness
How certain or uncertain do you feel that your project has a single right solution?
How certain or uncertain do you feel that you have to solve the problem as given to you?
How certain or uncertain do you feel that you have to just develop what was asked of you?
How certain or uncertain do you feel that you know the optimal solution?
Factor: Individual tentativeness / ill-structuredness
How certain or uncertain do you feel that you understand the problem?
Considering your project, have you had many or few opportunities to make decisions as a team related to your project?

We calculated descriptive statistics for each item and each factor. We conducted paired samples t-tests and correlation analysis to examine trends over and within each timepoint. We conducted in vivo qualitative analysis of students' responses to the constructed response items, grounding our coding scheme in the data [29].

Results & Discussion

We present our results organized by research question, and discuss our findings in light of the research on problem framing, agency, and engineering education. Our first question investigated how students in an intramural program perceived constraints, problem structure, and their roles in framing engineering problems, early in their projects.

Early in their problem framing, only 4% of students reported feeling restricted by the constraints of the problem, perhaps because 69% reported their problem was somewhat to very open. Students identified the following constraints: budget (40%), time (20%), access to resources, stakeholders, & spaces (20%), and their own capabilities (11%). Students frequently described solution requirements as constraints (38%) though in many instances these might be more appropriately framed as objectives that do not necessarily constrain the solution. The development of engineering requirements represents an important transition point in problem framing that moves the problem from a qualitative representation (e.g. needs statements, operating principles) to a quantitative one (i.e. metrics and values that reflect performance objectives and constraints). Students who overall lack of experience with ill-structured problems, and design problems specifically, have limited experience with this qualitative to quantitative transition that is common in practice. Another challenge among students is the development of representative metrics and setting an initial value (specification) for engineering requirements. Prior studies have shown that this challenge may be tied to low information seeking behaviors of novice designers [30-32] and a tendency to move from a surface understanding of the problem directly to concept development without developing requirements [31].

On average, students reported relatively high levels of shared and individual consequentiality, suggesting that they perceived opportunities to make consequential decisions even at the beginning of their process. Likely reflecting the earliness, they reported relatively few opportunities to learn as a result of these decisions. Students reported lower shared and individual tentativeness, suggesting that at the beginning, they anticipated that the problem would not change much. Past results have only assessed framing agency relatively late in the framing process, whether doing so using discourse analytic or survey methods [9, 10, 33, 34]. Our findings extend this past work and contribute understanding of framing agency and its development, suggesting that early design instruction can put students on a path toward developing framing agency. Based on their responses, even early in the process, students recognized their role as designers who make consequential decisions, even though they did not anticipate that their problems would change as a result. As others have found, inexperienced designers tend to not realize how much effort is needed to not just solve problems, but also to frame them [6].

As they considered the unknowns, students planned how they would make progress on their problem framing. At the beginning of their problem framing work, 65% of students explained they would do research (searches, review existing solutions, seek experts); 45% planned to meet their sponsors to clarify the problem; and 24% planned to observe, interview, or otherwise seek information from stakeholders. When we consider the kinds of sources students sought in doing

research, there is an emphasis on formal and expert sources, with students less commonly seeking out competing products or generating their own information, such as by testing or modeling. Students do not see underlying processes for solving ill-structured problems (i.e. the design process) as an iterative framework for generating knowledge that informs the (re)framing of problems and reduces uncertainty. Rather, their prior experience with predominantly well-structured problems conditions students to view such processes as prescriptive, sequential procedures for getting to the right answer. The emphasis on research and sponsors reflects the belief that much of the uncertainty about the problems could be relatively easily resolved. This aligns to research on inexperienced designers showing that, influenced by their past experience solving well-structured problems, they tend to expect design problems to be solvable using similar methods [14].

Our second question investigated how students' perceptions of constraints, problem structure, and their roles in framing engineering problems changed over the course of their participation in an intramural program.

After completing four months of work, 10% of students reported feeling restricted by constraints, and 74% reported that their problem was somewhat to very open. Compared to the beginning, both of these numbers are somewhat higher, suggesting that students tended to develop better understanding of design problems as ill-structured. Students identified the following constraints: budget (31%), time (26%), access to resources, stakeholders, & spaces (36%), and their own capabilities (33%). Students frequently described solution requirements as constraints (38%). This represents notable increases in access to resources, stakeholders & spaces, and their own capabilities (Figure 1).
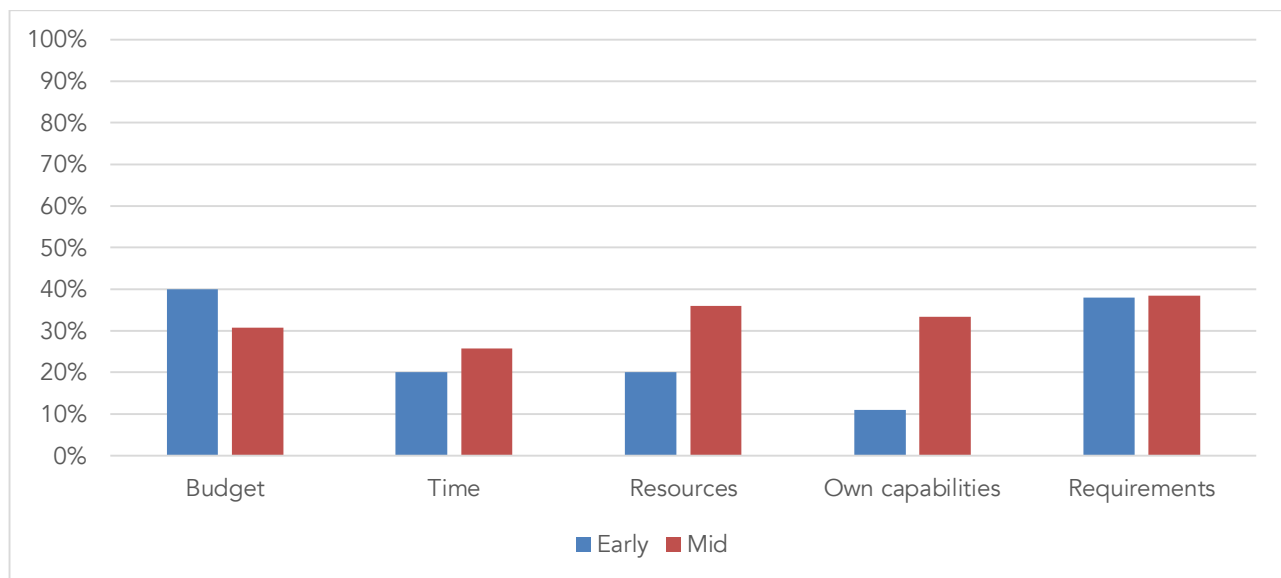

Figure 1. Percent of students who raised types of constraints early (in the first weeks) and mid (after four months of work).

While two students referenced the pandemic as creating the access issues ("Covid preventing us from regular access to tools and machines to use in the project"), most students' comments clarify that these concerns were about limited access to stakeholders' experiences; for instance,

one student explained, "Some constraints are physically being in Tanzania to get a better sense of the cultural and social needs. We also have no physical prototype to work with and our sponsors work in another country." Students provided specific examples of their own limitations.

Also of note is that some students described challenges related to uncertainty about specifications. For instance, one student mentioned, "Another constraint is how much activity our website will be able to host while still running effectively" and another wrote "Performance, this is the most important one. We need to reach a certain flow speed range, all the while meeting the building codes of such a velocity barrier or dam structure." Both of these design requirements involve sociotechnical estimation and depend on other factors, and, as with their early work, this reflects the struggle to turn qualitative information into quantitative requirements. Here, we also consider the value that practice with estimation could have. In their prior experiences, students would have lost points when reporting an answer without precision; this makes estimation appear untrustworthy. These challenges also reflect students' lack of experience with the problem domains and thus an inability to make estimates – even order of magnitude estimates – of relevant parameters in the problem space. These knowledge gaps could potentially be informed through discussions with stakeholders who either have the necessary expertise or could facilitate connections with those who do.

Later in the experience, students tended to report being more tentative about their own treatment of the problem (Figure 2, $M = 0.78$; $SD = 0.08$, scale of 0 to 1) compared to early in the experience ($M = 0.63$; $SD = 0.14$), and this difference was significant, $t(29) = 5.15$, $p < .001$, $d = 1.3$ (a large effect size). This suggests that the supports for problem framing and opportunity to work with a sponsored project provided opportunities for students to develop problem framing skills, to increasingly treat the problems as—even after they had spent months researching the problem—open to modification.
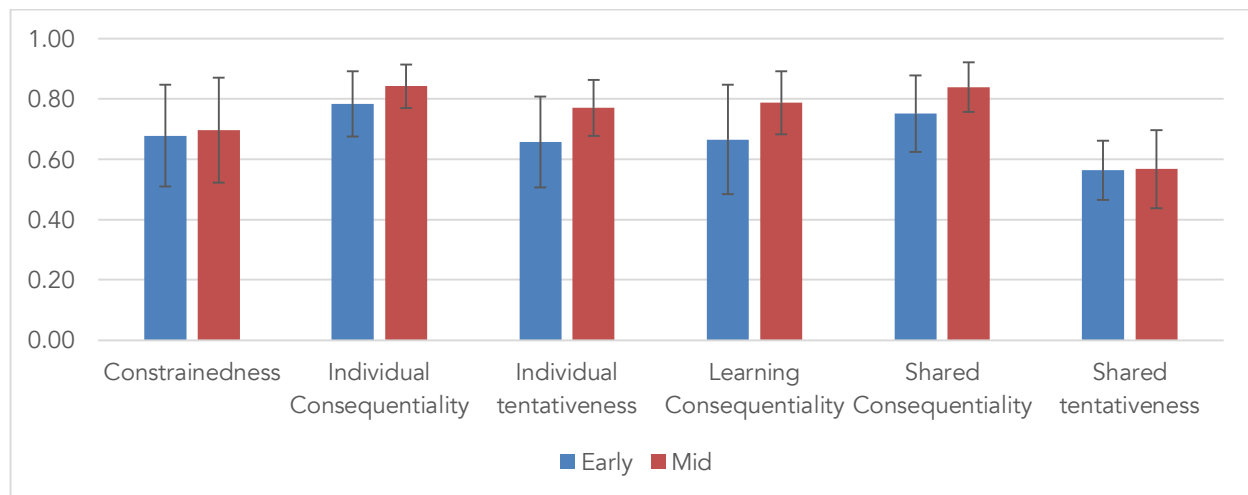

Figure 2. Average scores, normalized to a 0-1 point scale, for framing agency factors, early (in the first weeks) and mid (after four months of work). Error bars depict one standard deviation above and below the mean.

Unsurprisingly, later in the experience, students tended to report more learning opportunities as a result of decision making (Figure 2, $M = 0.79$; $SD = 0.10$, scale of 0 to 1), compared to early in

the experience ($M = 0.63$; $SD = 0.16$), and this difference was significant, $t(29) = 4.62$, $p < .001$, $d = 1.2$ (a large effect size). As they also reported increased individual and shared consequentiality—meaning, they saw their own and their teammates decisions as consequential to the problem frame—they also recognized that they were learning as a result of these decisions. Drilling down into the individual items, we see nearly identical averages, indicating that students reported learning from their own decisions and their teammates' decisions equally.

Students who reported greater learning from decisions also reported significantly greater experiences of constraint, ($r^2 = .48$, $p < .001$) and individual consequentiality ($r^2 = .39$, $p = .04$), with both relations significant and positive. Collectively, this suggests that design problems that were constrained, yet open enough for students to make individual decisions created learning opportunities for students. None of the problems were fully constrained, but some problems were under-constrained. It is important to note that students' reporting on their learning does not necessarily indicate actual learning, as student perceptions are not reliable indicators of how much learning has occurred [35]. However, their perceptions do provide evidence of opportunities to learn. Together, this suggests a *Goldilocks* problem space may be particularly beneficial for students, in which problems are somewhat constrained, leaving room for students to make consequential decisions.

After four months of work that included supports for problem framing and project planning, most students who responded to the second survey reported remaining uncertainties about the problem. To make progress, 54% planned additional research, 18% planned to seek feedback from their sponsors, and 31% planned to seek information from stakeholders, including by sharing preliminary solutions or prototypes. This represents a slight shift from the beginning, with less reliance on external research and more reliance on stakeholders. When comparing the students who provided responses on both the early and midpoint surveys, individual trends reflect a decrease in reliance on the client, with 30% of students who mentioned the client early not doing so at the midpoint. While this might reflect naivety in how much they could learn from sponsors, or that seeking additional information from sponsors might be a form of cheating, we also think this could reflect that students recognized the importance of seeking information from stakeholders, as 15% who planned to contact stakeholders at the early stage did not plan to do so at midpoint, but 22% who did not plan to do so early did plan to do so at the midpoint. There was somewhat less overall change in terms of doing research, with 26% percent who planned to at the early stage no longer planning to at the midpoint, and 7% who did not do so at the early stage planning to do so at the midpoint.

Overall, this suggests that students increasingly saw value in defining problems from stakeholder points of view. For instance, one student, early in framing, explained they would "do extensive research and see the design being used to better understand the issues involved," and later, explained, "see who uses the machine the most and design our curriculum for those who need the most instruction on how to use it." In some cases, this displayed a shift from a technically-oriented to more human-centered approach:

> Early: "I will learn more about this aspect by talking with the sponsor. Also, I can do research into the design of a laparoscopic robot and try to find resources that may give me more hands-on access to an actual product in the field that already exists."

Later: "I will learn more about it through further research, both my own and my group's, and by talking to surgeons or others who work with robotic laparoscopic surgery technology to get their feedback about the difference the addition of haptics to the robot makes. I don't know how I'll know I have enough information, but getting the opinions of people who use the technology will be a helpful addition to research to figure out the extent of the problem."

In the quotes above, initially the student envisioned their gaps in understanding could be filled by the sponsor, technical information about laparoscopic robots, and gaining their own first-hand experience with one. The recognition that it was not their own experience, but the experience of those who use such robots shows an understanding of why it is important to frame design problems from stakeholders' points of view. This aligns to research showing that engineering students tend to foreground technical aspects of design in their initial efforts to frame problems because this is what has been emphasized in prior coursework [18].

Conclusions
Overall, we found that even early in the intramural experience, students displayed aspects of framing agency but also reflected typical behaviors reported in the literature, including treating the problem as relatively well-structured and foregrounding technical over social concerns. With problem framing supports, students developed more sophisticated problem framing approaches, including valuing and relying more on stakeholder points of view. Students became more tentative in their treatment of the problem and reported more opportunities to learn as a result of their own and their teammates' decisions, and especially when they viewed the problems as somewhat constrained and reported being able to make their own consequential decisions about the problem. This extends prior work showing that students' understanding of problem types evolves in this intermural experience [36].

While past work on framing agency has been undertaken in required courses (first year and senior design) [10, 33, 34, 37], our study, set in a volitional intramural program, provided an opportunity to explore framing agency in a high agency environment that, in some ways, is more akin to the workplace. However, this volitional setting also brings limitations. While past research in courses could treat the survey as a required course assignment used for course evaluation purposes, we had no ability to make such requirements of participants. Paired with the challenges of the pandemic, we had a low response rate to our second survey. While we had a matched sample size sufficient for comparative statistics, we are not able to make strong claims that these responses are necessarily representative of those who did not complete the survey. Our future studies will explore incentives for survey completion, including making donations to groups like Engineers without Boarders for each survey completed.

While our results should be treated as preliminary, we share some implications. First, we found the framing agency survey [9] to be quick and easy to implement, analyze, and interpret, making it a viable additional tool instructors may include to monitor students' progress in problem framing capacity. Second, we added constructed response items focused on what students know, wonder, and plan to do to the survey to position it as a problem framing tool, rather than just an evaluation tool. The additional information in these answers helped us understand students' responses and feel more confident in the changes reflected in the quantitative data.

Because we found early indicators for an understanding of the need to make decisions, paired with a less tentative initial treatment of the problem, we argue that design education should foreground such experiences, providing opportunities for students to direct iterative reframing.

The results also informed planned changes to the intramural experience. First, we recognize a need to encourage and support the use of design methods focused on initial problem framing. For example, some intramural projects would benefit from reverse engineering, but students are either not familiar with this method or see it as inefficient to their problem solving. While students identified specific methods for problem framing from the Design Exchange (thedesignexchange.org) as part of the experience, the pandemic negatively impacted their ability to implement some of these methods. Second, the fall semester concludes with a formal problem statement from the students. In the future, we plan to have the students submit their problem statement at multiple points during the semester. This will make their evolving understanding of the problem more concrete. Finally, we plan to perform a closer inspection of the resulting project scope set by students, and will do so in collaboration with project sponsors or identified stakeholders. This change is necessary to ensure alignment between the students' understanding of the problem, their planned solution path and deliverables, and their current abilities. Although set in an intramural experience, we see many of these strategies as salient for design courses.

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