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Building Better Engineers: Critical Reflection as a High Impact Practice in Design Learning

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Abstract

Critical reflection is a deliberate process wherein students focus on their performance and practice and consider their thinking and mindset that led to particular actions, what happened, and what they are learning from the experience. Reflection as a practice in learning has been well-documented for its potential to cement knowledge. Because of this potential, reflection is valued as a tool for continuous improvement in learning. This work in progress describes a collection of data visualizations and reflection activities to foster the development of reflective engineers who equally consider their design learning, ability to function on teams, and identity development.

Engineering design is, by its nature, future oriented. Through design, engineers identify and solve problems. To achieve success in creating novel solutions to problems that enable better futures, engineers must embrace the complexity of the problem and iterate through design together with teams. Thus, the critical reflections described herein mimic this approach. The data visualizations and reflection activities in this study are structured to support opportunities for individual contemplation, team discussion, and instructor feedback. Students self-report design process data through a design diary where they record their activities as to a particular design project. The diary data is then used to generate visualizations that inform students as they engage in sustained, consistent reflection. These reflection activities are designed to situate students in contexts of productive discomfort to improve practice through developing a future-oriented frame. This frame is consistent with design, namely, to solve problems through collaborative iteration to create a better future. Since both individual and team-based reflection points are necessary for critical thought, this work has the potential to improve design learning, teamwork, and individuals' engineering identity. Supporting students through these difficult conversations using data and structured reflections has the potential to be transformative in developing a more equitable and inclusive culture wherein norms, behaviors, and mindsets are not assumed or left unquestioned. The intended outcomes of this work are to train students as reflective engineers who engage in nonlinear approaches to design and to proactively develop team cultures that value diverse experiences, views, and thinking all in service to creating a more equitable engineering profession and high-quality designs that benefit society.

Introduction

This work in progress describes a pilot to incorporate critical reflection activities, completed by individuals and by teams, during the implementation of design activities in an early-career, project-based learning context. As described in full below, critical reflection has been demonstrated as a high-impact practice that can deepen learning and cultivate a productive future-oriented mindset [1]–[3]. Thus, activities that incorporate reflection into projects have grown in use and garnered increased attention in engineering education for their transformative potential [4]–[6]. Further, consistently engaging in reflection on learning as a community has the potential to develop environments and classroom cultures that value student growth and community [7].

Critical reflection is a deliberate process wherein students focus on their performance and practice and consider the thinking and mindsets that led to actions, the order of operations, and the real-time lessons they learned from the experience. This process enables students to proactively think about their future actions in a way that deepens their learning. Reflection empowers learners by making them more active participants in the learning process, encouraging them to think about their development in a more critical way as they relate their actions to outcomes and gain proficiency in doing so with continued repetition [1], [8]–[11]. Importantly, reflection enhances the efficacy of active learning strategies and, thus, has a multiplicative effect [12]. In the context of engineering design, this is a powerful combination. The mindsets and processes central to reflection align with those of design, namely, to identify problems, ideate solutions, develop prototypes, test alternatives, and evaluate outcomes with a mind toward future improvements and opportunities. Just as design work is done by teams, reflection best happens when situated in community conversations where learning and the growth of all is valued [13]. As students engage in community-centered reflection, they practice the skills necessary to become lifelong learners and engineers who can create impactful designs that serve society's needs [12], [14].

In this work, we describe plans to extend our current pilot study [15] to include a set of critical reflection activities. Students will cycle through critical reflection activities to consider themselves and their own actions, themselves as a member of a team, and the team as a unit. The purpose of this cycle is to equip students to recognize how their own actions and mindsets contribute to project outcomes and team dynamics. In assuming responsibility for their own actions, they are prepared to address what they control and what they can influence both in service to their learning and their design efforts. These reflection activities are centered around data visualizations representing students' self-reported engagement with design phases, with activities, and with their assessment of team dynamics [15]. The goal of these critical reflection activities is to enhance student learning and practice of design and to engender equitable, positive team dynamics through which students design in spaces that inspire joy and creativity.

Active learning through practice is important in studying design but assuming critical reflection occurs automatically represents a missed opportunity for instructors to provide a deeper learning experience. When novice designers approach ill-defined problems, they often advance through the design process in a linear fashion or deliver designs representing only their initial ideas [16], [17]. While students may know that they are supposed to engage with the design process non-linearly, they frequently find the actual process amorphous and confusing. Furthermore, design efforts can be further hindered by the difficulties associated with working on teams such as interpersonal dynamics, implicit and explicit biases, and inequities in the shared labor. We aim to recognize and address these circumstances through both the individual- and team-based critical reflection activities. We anticipate that the difficult discoveries and conversations that result from intentional, critical reflection will prepare students to engage more effectively with the design process and will extend to shared teamwork situations beyond their engineering practice. Through this work and future investigations, we seek to answer the questions: (1) *How might critical reflections be deployed to enhance student learning of engineering design and team dynamics?* (2) *To what extent do data-centered critical reflection activities influence student learning, identity as an engineer, and ability to function on a team?*

Research Method

Site and Participants

Data is collected at a small liberal-arts institution in an early-program engineering design course taken by students in their first or second year. At this timepoint in their undergraduate careers, most students have not yet declared a major but typically enroll in this course to inform their choice of a major. In this course students learn engineering design, alongside a range of manufacturing techniques, as they solve ill-defined design problems on teams. Each team works to solve a problem requiring conceptual design and tangible, mechanical solutions. There are several student learning outcomes (SLOs) that inform the design of the course. In this study, we focus on a subset of SLOs related to deploying and sequencing design activities and to team dynamics. The engineering design SLOs that this work targets include: (1) **i**mplement a **d**esign process to solve engineering problems (**ID**), (2) **s**olve open-ended and ill-structured engineering **p**roblems (**SP**), and (3) recognize when it is necessary to **r**evisit design **a**ctivities to improve a solution (**RA**). The teamwork SLOs include: (1) **f**unction effectively on a **t**eam (**FT**), and (2) give and receive **p**rofessional **f**eedback (**PF**). In addition to these SLOs, we are interested in students' self-concept as engineers (**e**ngineering **i**dentify, **EI**) as indicated by their quantitative and qualitative assessment of the statement "*I see myself as an engineer*."

As teams engage in design work, they are also required to prepare (1) a team contract to establish norms, values, and logistics, (2) agendas for meetings with project clients and advisors, and (3) project management documents such as action-item logs. The participants in this study include students enrolled in the course. Participation in the study is voluntary.

Data Collection

All data is derived from students' (1) design diaries, (2) reflection activity assignment submissions, and (3) responses to pre- and post-term learning-outcome-aligned self-assessments and engineering identity surveys. For the design diaries, students self-report engagement with design phases and activities as described in our previous work [15]. Students report this data through a diary activity that is completed three times per week. This data is used to generate visualizations representing student and student teams' engagement with design. All quantitative items on the SLO and identity surveys and prompts are scored according to a five-point Likert-scale with a score of one being low (strongly disagree) and five being high (strongly agree). Additionally, students evaluate themselves and their team members on the teamwork focused SLOs prior to each discussion activity to generate a 2×2 matrix representing the team's assessment of each member. Students consider these visualizations during each reflection activity. Through each activity students respond to prompts through writing, in the individual reflection, through conversation, in the team reflection, and through written planned actions in both.

Data Visualizations and Reflection Activities

The goal of each design-process data visualization is to purposefully confront students with their self-reported deployment of design activities. Visual evidence of individual activity, instead of perceptions of activity, supports students in coming to terms with their practice and has the potential to break counterproductive cycles. The focus is not on the veracity of their self-reported engagement but instead on their reflection on their approaches to design. The purpose of these reflections is to equip students to be future-oriented by describing and understanding what is and has been and to plan for what could be.

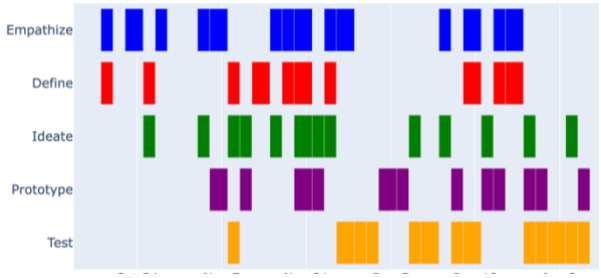

Figure 1: Prototype of Design Diary Visualization

Individual Reflection

The data visualizations for design phase and activity engagement are inspired by Atman's work [16], [17]. Figure 1 shows a data-visualization prototype using generated data representing design phase sequencing across time for an individual student.

In considering this visualization, students can identify the extent to which they have engaged with design in a linear, stepwise fashion as compared to a circuitous but purposeful path indicative of iteration and development. As students are presented with this visualization, they complete an individual reflection activity, shown in Table 1.

Students respond to writing prompts as part of this biweekly reflection and planning activity. Each reflection assignment is designed to be completed in approximately 30 minutes as a homework assignment. These reflections can only be viewed by the course instructors, for evaluation and opportunities for individual debriefing, and the student. This structure is intended to support students in being vulnerable and candid in their responses as they take ownership for their actions and plan for next steps.

Team Reflection

The team-based data visualization will mirror the individual visualization in structure. A prototype for this visualization is in development with the goal being to communicate the design work of the entire team while also indicating individual activity. This mirroring is intentional so that students can more readily process and consider the entire team's aggregated data while critically examining individual actions before engaging in discussion about the reasons, motivations, and consequences of their choices. In addition to the team's design-diary visualizations, the team will consider a visualization indicating each individual member's effectiveness related to the teamwork-centered SLOs as assessed by their team. An initial prototype of this visualization appears in Figure 2.

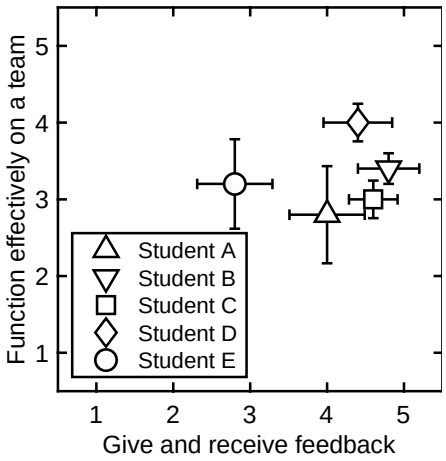

Figure 2: Prototype of the Teamwork SLO 2×2 Matrix

In considering these visualizations, students can collectively observe and interact with (1) their team's combined and individual member's deployment of design activities and (2) the team's dynamics. These features are important as they can surface inequities across the team and prompt conversations about the reasons for them (e.g., implicit and explicit biases, external circumstances, unhealthy team dynamics, etc.).

Table 1: Individual Critical Reflection Activity

Instructions: Individual Critical Reflection Welcome to this week's reflection activity. Before you begin responding in writing to the questions below, take a moment to consider the figure and recall your own actions and mindsets in your design work since your last reflection. After considering your own actions and mindsets, think about your team's work and interactions. Just as you empathize with those for whom you design, remember that it is important to empathize with those on your team. After you recall and consider your own and your team's work since your last reflection, begin your written responses to the Individual Critical Reflection questions below.

• Consider your engagement with design phases and activities since the start of this project.
  ○ How did the ways you've engaged in design affect the quality of your deliverables?
  ○ How have you identified which design phases and activities are most appropriate to pursue next?
  ○ How have you helped your team appropriately identify and effectively switch among design tasks?
• Consider your team's dynamics. How do you, as an individual, contribute to your team's effective function?

Instructions: Individual Action Planning Now that you've reflected on and responded to actions and mindsets, plan for the next two weeks. As you plan, consider continuing what is working well and improving what is not yet working well. Don't neglect to review your prior reflections to inform your current thinking. Lastly, remember to center your planning on what is in your sphere of control.
• What specific mindsets, activities, and approaches will you continue and/or incorporate into your engineering design work to enhance your learning, design deliverables, and team dynamics?

The goal of this discussion is to improve the team's design deliverables while also driving the team toward increasingly healthy and productive team dynamics. The team can identify how the group can collectively improve their practice while also finding joy in shared successes and valuing individual contributions and learning. During this activity, teams discuss each prompt. Discussions will occur biweekly. This reflective discussion, which occurs during class, takes approximately 30 minutes. During this conversation, the instructors may be present in the space but are not a part of the conversation. Students submit their discussion minutes and revised team documents for instructor review. These items are discussed with the instructor during project advising meetings.

Data Analysis

In the short-term, we will assess the impact of the described critical reflection activities on the previously identified learning outcomes and students' self-identification as an engineer (described in Site and Participants). In the study, to date, we have collected pre- and post-term data for a semester in which no design-diary data was collected and in which no reflection activities were completed (phase 1, Fall 2021) and pre-term data for a semester in which design-diary is being collected but in which no reflection activities are conducted (phase 2, Spring 2022). These results appear in Figure 3. The pre- to post-survey data (Figure 3a) are compared using a Paired Samples t-test. From these preliminary results, we see that students are making gains as to their learning of engineering design and that there is limited, but significant, growth related to engineering identity. The term-to-term pre-survey data (Figure 3b) are compared using an Independent Samples t-test. Students' responses to qualitative items, not reported here, such as individuals' written-reflection responses and pre- and post-survey items, such as "I DO/DO NOT see myself as an engineer because…", will be encoded using inductive thematic analysis. Themes identified from this work will be used to inform and challenge conclusions derived from the quantitative analysis and to inform the design of critical reflection activities in future terms. Furthermore, students' written responses are likely to elucidate the connections between design and critical reflection activities with students' multifaceted identities. By including and considering qualitative data, we gain access to the motivations behind students' actions and their thinking as it relates to quantitative self-assessment. It is our hope that these combined efforts will elucidate unforeseen design and implementation issues and support future iteration in service to student learning.

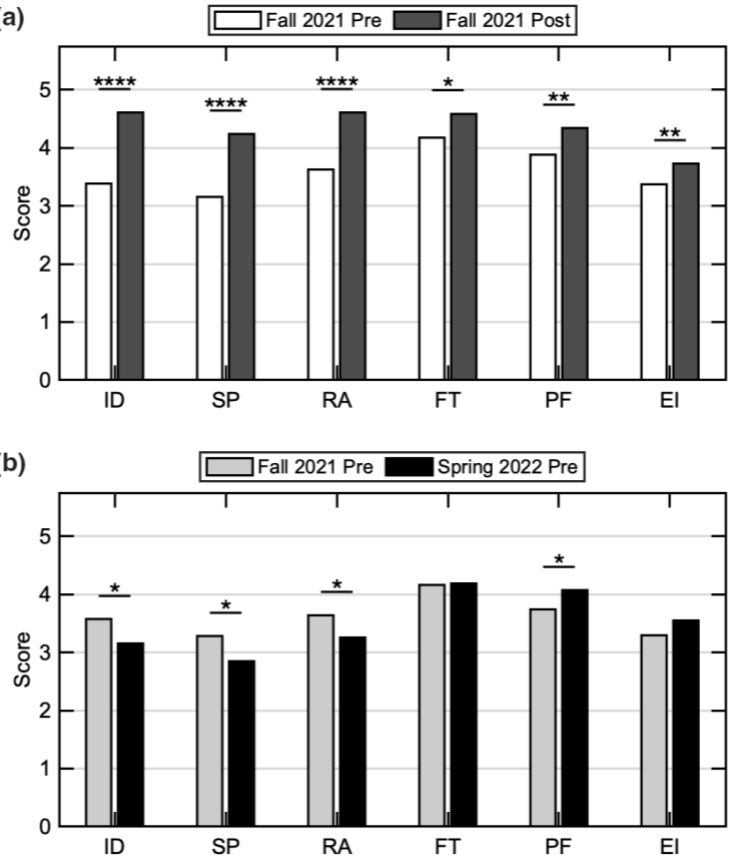

*Figure 3: Comparison of Students' Self-Assessment for SLOs and Engineering Identity. (a) Fall 2021 Pre- and Post-Term Matched Pair Analysis, $n_{SLOs}=49$, $n_{EI}=41$. (b) Fall 2021 Pre- and Spring 2022 Pre-Term All Responses, $n_{Fall2021,SLOs}=72$, $n_{Spring2022,SLOs}=56$, $n_{Fall2021,EI}=61$, $n_{Spring2022,EI}=54$,. Significance is indicated as follows: $p<0.05$, *; $p<0.01$, **; $p<0.005$, ***; $p<0.001$, ****.*

We will use the data generated from this pilot study to begin to answer our question regarding the extent to which data collection and data-centered critical reflection activities influence student learning, identity as an engineer, and ability to function on a team. In deeply analyzing

the qualitative data, we will be equipped to iteratively improve these reflection activities and learn how we might enhance the design and implementation of critical reflection activities to transform student learning, development as an engineer, and the ability to lead and contribute to the function of effective teams.

Table 2: Team Critical Reflection Activity

Instructions: Team Reflection/Discussion
Welcome to this week's team reflection and discussion. As you think about joining in conversation with your team, remember that it is important to empathize with your team members. Sharing and receiving feedback can be difficult so be sure to give space for everyone to speak and listen.

Before you all begin discussing the questions below, initially take five minutes (1) to review each figure and (2) to recall your own actions and mindsets in your shared design work since your last written reflection and team discussion. After considering your own actions and mindsets, think about your team's work and interactions.

After you recall and consider your own and your team's work since your last reflection, regather as a team. Identify someone to record minutes and begin your conversation using each of the prompts.

- Are we, as a team, working in a way that:
  - Respects everyone?
  - Is equitable?
  - Values everyone's contributions?
  - Value's everyone's learning?
- Are we, as individuals on a team, effectively giving and receiving feedback to function more effectively as a team?
- Are we, as a team, effectively deploying design activities to (1) successfully complete the project, and (2) value each team member's learning?
- In approaching our shared design work going forward:
  - What practices do we keep?
  - How do we change our practice to improve our learning, design deliverables, and team dynamics?

Instructions: Shared Planning
Now that you've discussed your team's shared work and dynamics, consider how you might continue doing what is working well and improve what is not yet working well. Translate your discussion into actionable outcomes by revisiting each of the items in the following prompts.

- Integrate the outcomes of your team's discussion into your team contract (new values, norms, and commitments), agendas (consistent discussions and accountability), and action items to translate the outcomes of your discussion into action.
- Prepare to share the summary of your conversation with your advisor during the next meeting.

Anticipated Results

We seek to determine the differential impact of self-reporting design activities alone and together with reflection on student teams' ability to solve ambiguous design problems [15]. For the SLOs considered here, we anticipate that merely reporting engagement in design activities will not result in a meaningful shift in student growth of or perceptions about their abilities, learning, and identity. This hypothesis will be answered at the end of phase 2.

In the next academic term, we will include the critical reflection activities described in this work (phase 3). We expect that engaging in data-informed critical reflection will result in significant growth along each of these SLOs and hypothesize that supporting students in critically engaging with team-based design through reflection will cement learning. Furthermore, these reflections can support the development of self-critiques during decision-making thus establishing students on a path of continuous improvement as members and leaders of teams and as engineers. We also hypothesize that the combination of team reflection and follow-up conversations with the instructor is likely to reduce the tendency for students to signal that all is well with a team when that is not the case. Instead, we expect that students will collectively identify problems and circumstances within the team to proactively address tensions together and develop shared language to debrief them with the instructor. This cycle is likely to challenge students to approach design as a cohesive unit. Thus, these shared critical reflections may also serve to improve dynamics and thus strengthen community ties. In this case, we may observe gains in student self-reported identity as an engineer. One possible risk is that the range of student demands across their academic programs or lack of buy-in may dilute the impact of reflection activities.

Discussion

Learning and teaching design is difficult. This difficulty in learning design is often exacerbated by fraught team dynamics which can be amplified during stressful points of the academic term. While teams can be a source of joy and community, they often present contexts for contention that detract from learning and that foster isolation. Through this work, we aim to focus on design learning and team dynamics together to reinforce practice in both areas through collaborative, critical reflection. Importantly the activities we describe can be readily reformed to any design-learning context by modifying the design phases and activities of interest or by focusing on other high-impact SLOs. Consequently, these tools can be applied to learning across the curriculum. As students individually consider their choices in engineering design work and their interactions on teams, they are prepared to deploy design activities more effectively and collaborate with their team to generate improved designs and deepen their learning. This advanced learning in the context of an early-career design class is important and necessary because it equips students to be critical about their development and practice as engineers while also considering how they can contribute to better functioning, productive, and more joyful teams. Authentic engagement in these efforts prepares students for future success in design work throughout their engineering careers.

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