Board 332: Learning by Evaluating (LbE): Engaging Students in Evaluation as a Pedagogical Strategy to Improve Design Thinking

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Navigating the engineering design process is a central aspect of K-12 technology and engineering education. Students are presented open-ended design challenges and given the opportunity to generate ideas, make decisions, and present their solutions. However, a traditional approach to this assessment in design, with fairly independent (or group) work and then presentations at the end of the project, limits student learning because learning is seen to stop when the assignment is submitted for evaluation. In this paradigm, evaluation is solely the responsibility of the teacher. Furthermore, even if students gain new ideas from their peers' presentations, these insights cannot be capitalized on because sharing these examples culminates the project and the class moves on from the design project.

Instead, our project is developing, refining, and testing a protocol in which students evaluate prior work to prime them for learning while designing, through what we call Learning by Evaluating (LbE) [1], [2]. This approach introduces two important changes to the currently practiced paradigm: 1) actively engaging students—in addition to the teacher—in the critique and evaluation process; and 2) performing this evaluation of example work prior to embarking on a design task, as opposed to review at the end. In making these changes, we prepare students to internalize what it means to make a high-quality design and be able to immediately apply what they have learned (see Fig. 1).

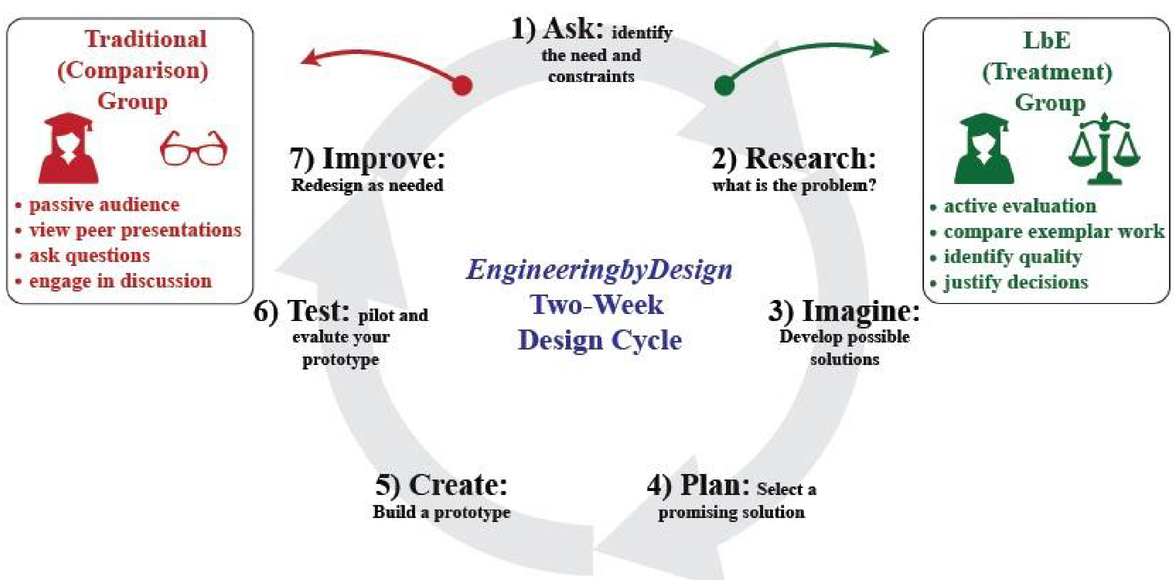

Fig. 1. Typical curricular approach to teaching design process with differentiation between traditional and LbE treatment group conditions.

In brief, the LbE instructional approach introduces students to a comparison process of existing artifacts prior to beginning a design project. Students are shown example work in all levels of quality, two at a time, where they must explore, decide, and justify which example is higher quality. The collection of artifacts and the decision prompt (called the holistic statement) are determined by the instructor to emphasize key features of the design challenge of learning outcomes related to the design thinking process. Importantly, during these comparative judgments, one example may not be better than another in every aspect; rather, there may be tradeoffs in the two designs, reinforcing the critical thinking practices necessary when designing [3], [4]. After students make several comparisons, a class discussion is held to share merits of the various examples and build consensus about key design values for this context. Finally, students proceed with the design work, integrating what they have learned and building off of the ideas they have seen.

Our past independent professional implementations and research with this approach have engaged college and middle school students [1] [5]. Yet, the focus on design thinking present in these settings is relevant and appropriate for students of all levels. Our project broadens the reach of the LbE approach by partnering with high school teachers and students in first year engineering courses in the Atlanta, GA area. For the Foundations of Technology (sometimes called Foundations of Engineering) classes in these settings, the design process is a repeated framework, giving multiple opportunities for our project to implement and learn from the comparative experience. In the first two years of the project our approach is following a design-based research strategy [6] -[8][8][8][8][8][8][8] to demonstrate the feasibility of widespread implementation beyond our team and make improvements in the LbE approach. The third year of the project will use a quasi-experimental design to compare the traditional approach to implementation with LbE as a primer for design learning.

This paper and poster briefly describe the underlying theories motivating this work, and several of the lines of inquiry we have taken in the design-based research phase thus far—both toward feasibility of preparing and implementing LbE and fundamental understanding about the ways in which students exercise critical thinking in design. Through the first two years of our project we have furthered progress towards the sustainability of the LbE experience through 1) introspection on our past approach and initial strategies for preparing the comparative sessions, 2) classroom observations and reflections with teachers, and 3) analysis of student justifications made during the comparative sessions. All together, these activities have prepared us for progress in the next phase of investigation about the efficacy of learning by evaluating.

Theory of Action: Why LbE?

Building on our pilot work with students, our theory of action is that the experience of comparing example work 1) meaningfully supports students' design thinking mindset (helping students think like designers), 2) critical thinking and reasoning (helping students to make and explain decisions), and 3) ultimately their design performance (as students apply their thinking). These three variables are critical in the Next Generation Science Standards (NGSS) [9] and Standards for Technological and Engineering Literacy (STEL) [10].

Professional development trajectories involve both epistemic—learning how to think—and ontological practices—learning how to act [11] – [13]. Specific to becoming a designer, the shifts often come from reflection on the practices and process [14], [15]. Ways of thinking about design also become more expansive. Daly et al. [16] characterized these shifting ways of thinking about design as a shift from design as a decision-making process (which we are scaffolding) to one associated with freedom.

Furthermore, the conceptual development from beginner to professional designer follows the central variables of our study as students learn how to think and apply reasoning. In the first step, students must learn patterns of thinking. We reason that the comparative experiences in this innovative pedagogy will allow students to solidify their own understanding of the content, context, and ways of thinking for an assigned project. For example, students learn to emphasize key values for a design including holistic thinking, openness to new ideas, and perspective taking [17]. Then these are applied in decision-making and argumentation as students identify strengths and weaknesses of various examples [18]. Finally, the new levels of thinking and reasoning continue to be applied and infuse design performance.

Instructional Approach: How to LbE

Our structured approach to implement a LbE comparison session has developed from our initial conjecture, based on our own reflection, professional development sessions and discussion with teachers, and observations of the experience in practice. The approach is designed to support students' evidence-based decision making and engineering argumentation—the process of making and justifying claims. While a number of theoretical justifications may be made for a given lesson strategy, several aspects of the experience are aligned with the patterns of cognitive apprenticeship [19] and epistemological foundations for engineering argumentation [18]. Students' abilities to see what matters in the design process, and form arguments to that effect, are strengthened by this integration with theory. The instructional approach is elaborated here, in several phases, which proceed through the preparation of the experience to its implementation in a classroom. As these are explained, brief attention is given to ways in which this strategy aligns with the just mentioned epistemological practices.

Preparation for the experience includes 1) identification of the learning outcomes or topic of interest; 2) identifying the holistic statement criterion by which students will compare artifacts; and 3) curating a collection of relevant artifacts. The learning goals may correspond to principles of design or technical aspects of the class, though taken together, the comparison experience will be most effective when it engages students in comparisons with subjective answers. Therefore, the holistic statement should align with the desired learning outcomes and guide students to explore this open design space. We have a number of outstanding questions about the types of artifacts to use, though there is evidence that the quality of artifacts—whether they are "good" or "bad" examples—does not seem to matter as much as the comparison experience [20]. We are using a digital interface called RM Compare (https://compare.rm.com) to facilitate the experience, but alternative strategies may permit the same learning outcomes (see Fig. 2).

Classroom implementation includes 1) teacher introduction and modeling; 2) student comparisons and justifications, which are digitally cataloged; and 3) class discussion. As the teacher introduces the design project to their class, they may begin with a sample comparison and think-aloud explanation of what matters in the design context. Students proceed to make several comparisons and explanations for each selection. Because LbE is a primer for learning, students may not have sufficient abilities to make comparisons or gain insight without

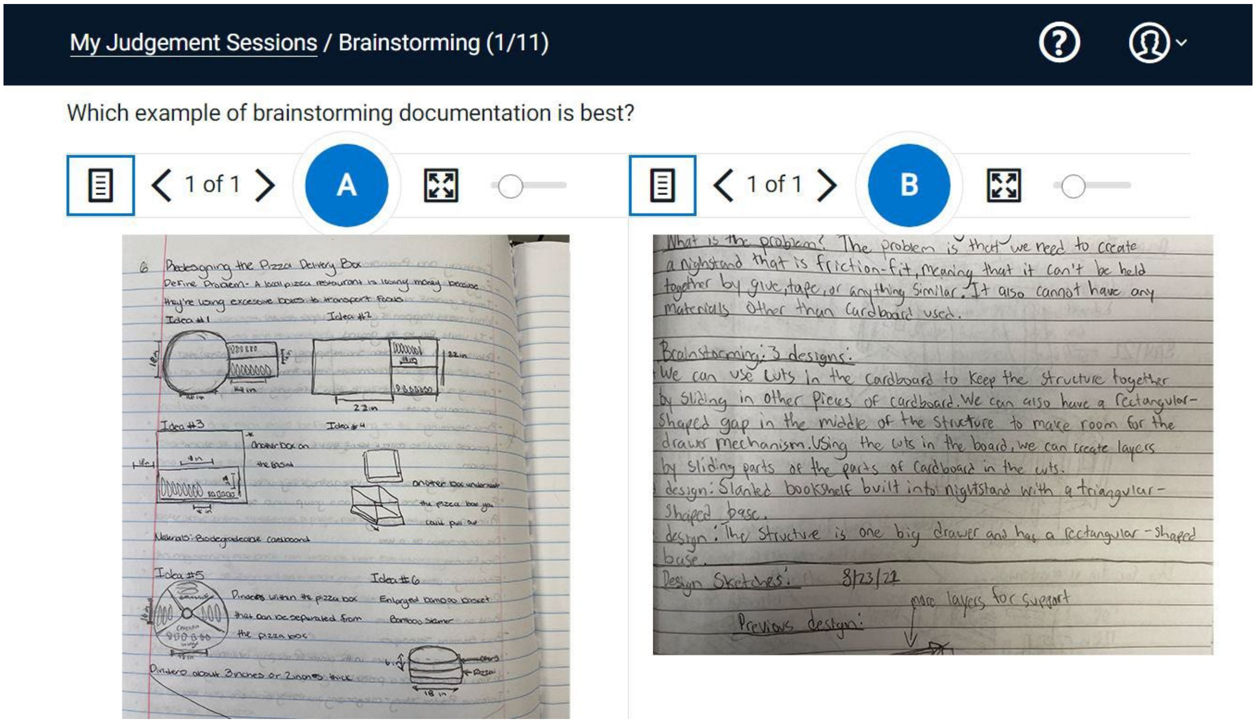

Fig. 2. Typical curricular approach to teaching design process with differentiation between traditional and LbE treatment group conditions.

preparation. However, teacher modeling and classroom discussion can help students begin to see what matters. Also, because pairs of artifacts are presented side by side in the digital interface, students are able to compare and contrast and are more likely to recognize key features of the design that do or do not work [21]. When making and explaining the decisions (either independently or in the class discussion), students also adopt perspectives related to the design and reflect on parameters of the scenario therein. These activities especially follow literacy and oral practices for supporting engineering argumentation [18].

Project Findings from Design-Based Research

Our approach in the early years of the project has been highly compatible with the tenets of design-based research given 1) our authentic research context, 2) intent to inform changes to practice, 3) collaboration—as a team and also with teacher- and student-participants, and 4) ability to produce successive iterations in the instructional innovation [7], [8]. Several prominent developments in the instructional approach, and contributions to understanding students critical thinking while designing are briefly explained here.

Instructional Feasibility

In order to bring clarity to this instructional process, we began by reflecting on the process undertaken in our own instruction to identify patterns in the process. This self-reflection led to an initial formulation of the approach, which has been documented and refined as we have introduced teacher-participants to the approach. This process of preparation, comparisons, and discussion was described earlier in the Instructional Approach section of this paper. Tangible developments meant to support feasibility also included an LbE planning template, which gives space to record the teaching elements we have identified. As we have developed new comparison sessions for classroom use (on our own or with teachers), we have leveraged these templates to guide our thinking. The template serves as a generative tool by eliciting thinking about the instructional experience. For example, debrief questions are organized to help teachers align key concepts with conceptual, technical, and transfer-learning elements (see Fig. 3).

We have observed challenges to teacher time in preparation for the comparison sessions, although it has gotten easier with practice, based on our experience and observations. Therefore, we have also begun developing a shared library of comparison sessions with a completed instructional planning template and set of images. From browsing this library, teachers may see sessions that focus on the desired learning outcomes, or sets of images which may be adapted to fit the learning needs. We are still exploring the level of flexibility afforded by a given set of images—we do not know how the same images with different holistic prompts will work to further design thinking. Also, we do not know to what extent the LbE sessions can be applied in other teaching situations (though general sessions on design thinking principles seem applicable elsewhere). It is possible that the lifespan of these sessions coincides with each class project, and therefore, when the project changes, the LbE session needs to be updated.

Design Journals

Key Concepts:

Design journals document your design process to establish originality for patents.
Design journals show how you worked through the design process to establish credibility for your work.
Design journals allow you and your team to share ideas.

Potential Holistic Statements:

Which journal example documents ideas better?
Which journal is more credible?
Which journal could allow your team to continue working without you if you were sick today?

Link to artifacts folder: [url link to cloud storage]

Debrief Questions:

Conceptual:
- Why do we use design journals?

Technical:
- What are key features of good journals?

Transfer:
- What will your design journal look like?
- What will you put in it?
- Does your design journal look like the best journals shown? If not, what could you change?

Fig. 3. Example completed template for LbE session on design journals.

Classroom Observations

Observations of the experience in teacher-participants' classes have been instrumental for our team to understand how the LbE experience can be a cohesive part of design-based learning. While instruction during these observations was influenced by the professional development training that teachers received from us, in praxis, the translation of this approach through each teachers' professional judgment has led to unique experiences and insights.

Divergent and Convergent Thinking through LbE. In particular, from reviewing teachers' session creation, we noticed two distinct trajectories in thinking that were cultivated by the LbE session—to diverge or converge in design thinking. For success in design, both divergent and convergent thinking strategies are needed [22]. It is helpful to see the utility of these LbE sessions to support multiple thinking strategies during the design process, even with their timing at the beginning of student work. While most teacher-created sessions utilized either divergent or convergent thinking, the flexibility of some sessions allowed for both strategies to be used. This often depended on how teachers approached the discussion or student interpretation of the purpose. (We identified these mixed sessions by student comments moving in both directions from the same class and session.)

A divergent session had the purpose of encouraging students to think about their design project in a creative way. Students might have been prompted to select which image could inspire their design work and asked to explain why. In this type of session, the artifacts tended to include a wide range of items, some even distantly related to the design project (further discussion about students' abilities to apply these to the design follows below). On the other hand, in a convergent session, the goal was to determine what "good" design looks like. Prompts might encourage students to identify which sketch best communicated design intentions. The debrief conversation tended to elucidate key features of good sketches, such as dark object lines, dimensions and annotations, auxiliary views, clarity, and so on.

Emphasis on the Introduction and Debrief Phases. Observations, in general and about the utility of LbE specifically, have magnified the importance of the LbE introduction and debrief phases for our research team, because various thinking strategies may be supported by the LbE sessions. These phases of the LbE instructional process are important to activate student thinking and situate the experience in the broader arc of class design projects (as opposed to a menial task to check off). Indeed, when students begin a session without adequate preparation, their reasoning about each choice is limited. In these cases, students tended to question the purpose of the experience and its application to their ongoing design work, or answer superficially. An effective debrief is necessary to develop consensus about design values as a class, address misconceptions, and reinforce the need to think critically about student design and the examples they see.

Students' Critical Thinking

Our project also contributes to fundamental questions about the critical thinking and decision-making of beginning designers, while simultaneously exploring how to support these thinking processes. By examining student comments made during the comparison session, we are able to approximate their critical thinking. We have conducted analysis of student comments from the first year of the project in two ways so far, and will continue to appraise student engagement with the LbE sessions.

Sentiment Analysis of Student Comments. Using a subset of student comments from different classrooms but all focused on the same artifacts and holistic statement, our team has examined how students' reasoning differed when comments related to the items they selected or did not select [23]. In some cases, students may provide a rationale for selecting an option (e.g., "I like Option A because it looks fancier"); alternately, the explanation may point out limitations of the other item (e.g., choosing Option A because "Option B cannot carry a thing."). We applied a sentiment classifier (NLTK Vader [24]) to determine the degree that each comment was positive, negative, neutral, or compound. Our findings showed a statistically significant difference in the positive sentiment score when students referred to selected options, $t(146) = 5.87$, $p < .01$. However, whether student comments related to the selected option or the not selected option, students used similar levels of neutral and negative words in their reasoning.

A closer look at students' positive comments revealed that students used shorter comments to give evidence for selecting an option. The low number of compound comments also upholds other evidence that beginning students tend to use few reasons when making an argument [25]. This may be due to the lack of critical thinking or reflection, or may result from failing to articulate their thinking in the comments (in spite of in-depth reasoning). Importantly for design, this represents an opportunity for instruction around tradeoffs and robust reasoning in the design process. There are also some contextual aspects of design communication that may limit this analysis—for example, in some cases, language seemed to be misclassified based on the design needs (e.g., putting "no strain" is actually a positive feature, despite the negative terminology).

Content Analysis of Student Comments. Another tactic has been to apply qualitative content analysis of beginning designers' justifications, to examine the types of evidence and reasoning applied [26]. Students' methods for developing an argument and the content of the argument itself offer fundamental insights into students' critical thinking while designing. We used prefigured codes, based on two prior studies about the nature of student explanations in engineering [18], [27], to label student comments.

An initial review of about 50% of the comments showed student attention to aesthetic, communication, and usability were the highest. Most comments attended to these visible elements of the design, by a wide margin. It is possible that other types of inference and evidence (e.g., marketability or originality of an idea) were less common due to the extended thinking required. It is also possible that these "visible" codes represent language that is accessible to students who are still learning the language of design—and that the LbE debrief may be a venue for instruction on these types of arguments.

We also noticed that the design context, holistic statements, and sets of artifacts play a prevalent role in the types of arguments made by students. For example, in a comparison session about graphic design, students' attention was expectedly turned toward aesthetic. The few examples where "scientific principles" emerged as a justification all related to a CO_2 car project. And the comments coded as "ethics" all seemed to stem from a single controversial image. It is appropriate for different design situations to reflect different needs and values. However, the alignment between students' critical thinking and these contexts suggests that care is needed when determining the challenges we use in class, preparing an LbE session, and orienting students' critical thinking. One promising possibility of the LbE sessions would be to direct critical thinking and reasoning to important areas of engineering argumentation that are otherwise missed by beginning designers.

Students' Thinking Transfer. Furthermore, we have made an effort to investigate students' abilities to make sense of the images they are seeing and transfer them to the design project at hand [28]. The capacity to abstract ideas from one item to another significantly impacts creative and design abilities [29]. When preparing for a backpack redesign challenge, one teacher curated a set of artifacts with both near- and far-transfer opportunities for how to carry things. For example, there were images of backpacks and handbags, but also examples of animals carrying their young that might lead to biomimetic designs. Within the comments and comparison results, it was clear that the capacity to recognize transfer was not an automatic process for students, even when designing creatively. Some students made comments that illustrate the value of using analogy and transfer in the design process, but the majority of students chose near-transfer items over far-transfer items. Student comments even expressed confusion over the inclusion of far-transfer items. Given the value of adaptive thinking in design, these findings have reinforced the need to scaffold opportunities for beginning designers' transfer and analogical thinking.

Taken together, these lines of inquiry related to student comments are uncovering how beginning designers approach engineering argumentation, critical thinking, and reasoning. These examples have illustrated to our team and teacher partners how further educational intervention may be required to facilitate logical, detailed, design-based reasoning, which can be bolstered by the LbE experience.

Conclusions

We are continuing to build an empirical case for the LbE experience after demonstrating its feasibility. The steps we have made to scaffold the instructional design of an LbE experience have helped us to bring new teacher-participants into the study, however this has been especially urgent due to changing teacher schedules and attrition of our initial set of partners. Having concluded the second year of the project, we are looking ahead to a quasi-experimental design that will contrast the LbE experience with traditional design-based instruction. We are optimistic that by examining student design work and their explanations and reasoning, we will see an articulable difference in the degree of their critical thinking and reasoning, as well as their adoption of a design thinking mindset.

Design requires the ability to evaluate and integrate knowledge from various disciplines and sources. While designing, students also make frequent decisions that exercise their critical thinking and reasoning. The LbE instructional approach described in this paper and being explored in our study represents an opportunity to support students in this process.

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