Priming the design process:

Activating and characterizing students' critical thinking in design

Andrew Jackson[1], Scott Bartholomew[2], and Nathan Mentzer[3]

[1] Workforce Education and Instructional Technology, University of Georgia

[2] Technology and Engineering Studies, Brigham Young University

[3] Technology Leadership and Innovation, Purdue University

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Abstract:
Design is a central activity of technology and engineering education in K-12 environments, as evidenced by its inclusion in the Standards for Technological and Engineering Literacy. Decisions are scattered through the design process, each with influence on the nature and efficacy of final outcomes. When made critically, these decisions can help students to generate ideas, narrow down which ideas to pursue, and be used to produce effective solutions. On the other hand, little scrutiny to the process can result in students being off track or developing ineffective solutions.

As an instructional innovation called Learning by Evaluating—to support students' critical thinking and decision making in the design process—we engaged students in a primer to the design process using comparative judgment. In the comparative judgment experience, students compared existing design work and were challenged to explain which of each pair was a better example before starting their own design work. Seven teachers in a large, urban school district participated in the project with their Foundations classes (9th grade) and administered comparison experiences over the course of a year.

The purpose of this qualitative content analysis study was to examine beginning designers' decision justifications made during the Learning by Evaluating activity in the beginning of the design process. We corroborate the theoretical foundations for the instructional approach using a framework for epistemic practices in engineering argumentation by Wilson-Lopez et al. (2020). These findings demonstrate how the practices of comparative judgment might support students' abilities to make and explain decisions. Next, using codes from Wilson-Lopez et al. (2020) and Scott Ronald Bartholomew et al. (2019) which both examined argumentation in the design process, we characterize the focus of students' critical thinking when justifying decisions.

Empirical evidence of students' process to develop an argument and the content of the argument itself offer fundamental insight into how students approach and reason through decisions in the design process. Attention to these decision processes can support design instruction in technology and engineering education. By characterizing which features of designed products students are attentive to, we can come to understand intuitive values in the design process and opportunities to teach those other 'designerly' ways of thinking. The findings of this study will also be used to inform future iterations of the Learning by Evaluating instructional innovation in order to optimize the approach.

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Introduction

As students proceed in the design process, they make decisions that influence the nature and efficacy of final outcomes. When thoughtful, these decisions can generate more ideas, narrow down which ideas to pursue, and be used to produce effective solutions. On the other hand, little scrutiny to the process can result in students being off track or developing ineffective solutions. Indeed, "making and explaining knowledge-driven decisions," "using design strategies effectively," and "integrating and reflecting on knowledge and skills" are key performance dimensions in design and learning objectives in design (Crismond & Adams, 2012, p. 745) that shape the trajectory of the process. In design education settings this might mean that students' design work does not match the value standards or requirements of the instructor or hypothetical stakeholders, or that students poorly prioritize design tradeoffs, or that students' overall growth in design is stunted because they are not learning through the process.

Another frame on these performance dimensions in design thinking is that they are examples of how critical thinking occurs in the design process. While "Design" is a core standard in technology and engineering education, the Standards for Technological and Engineering Literacy (STEL) also include critical thinking among the range of skills needed to successfully carry out design (International Technology and Engineering Educators Association [ITEEA], 2020). In the STEL, critical thinking is defined as "the ability to acquire information, analyze and evaluate that information, and reach an informed conclusion or answer by using logic and reasoning skills" (p. 152). Students will need problem-solving and innovation related to design in the future of work, and the cognitive reasoning practices we mean when we talk about critical thinking will support other processes as well, not only design.

Supporting students' growth as designers and critical thinkers may be implicit, through practice experiences designing, however clear learning experiences that foreground reflection on process and critical thinking skills are also important. In design education, Lawson and Dorst (2009) note that familiarity with design can span different levels. One level includes familiarity with the various design steps and improving project performance. This includes project-oriented practice that is "mimicked in the educational environment" (p. 62). However, another vital part of design thinking is to "step back from the hands-on level of working within the project to reflect on what they are doing" (p. 62). This explicit attention to process enables strategic thinking and a more refined approach to design problem solving. Similarly, advocates for critical thinking have recommended explicit instruction and practice of in critical thinking skills (Facione, 1990). In specific studies (e.g., Heijltjes et al., 2014; Marin & Halpern, 2011) and in meta-analysis (Abrami et al., 2015), empirical evidence has indicated the benefit of explicit instruction and practice compared to when critical thinking is implicit in class content. However, these reviews have also shown promise in instructional benefits for critical thinking across grade levels, disciplines, and even through brief instruction (Abrami et al., 2015).

As a means to support beginning designers' critical thinking and reasoning we are developing an instructional approach called Learning by Evaluating (LbE). The LbE approach uses comparative judgment and class discussion to model effective decision making and justification, stimulate critical thinking, elicit student decisions and justifications, and synthesize design values early in the design process so that students are able begin having activated their higher-order thinking (Bartholomew, Mentzer, Jones, et al., 2022). By beginning design work with these insights, we expect that the instructional experience can inform students design thinking and will ultimately improve their design performance. As we have iterated with the approach, our intent is to keep it theoretically grounded and empirically verified.

The purpose of this qualitative content analysis was to characterize beginning designers' critical thinking by examining their decisions and justifications from the LbE experience at the beginning of the design process. Student methods for developing an argument and the content of the argument itself offer fundamental insights into how students approach and reason through decisions in the design process. Outside this insight for the design educators generally, these findings will play a role in informed iteration of the LbE experience to optimize student learning. This research begins with a conceptual background of critical thinking and reasoning in engineering. Next, we describe our vision for the LbE approach and its intended supports of critical thinking. Finally, evidence of students critical thinking from early implementation of this pedagogical approach are analyzed to examine whether the instructional processes support critical thinking as theorized and to characterize the content of students' decision justification.

Critical Thinking

Critical thinking is widely called for, including in various instructional standards such as from the Next Generation Science Standards (NGSS Lead States, 2013); International Society for Technology in Education (ISTE, 2007, 2016), and the STEL (ITEEA, 2020) as mentioned above. Critical thinking is also among the "4 C's" and 21st Century Skills that are needed for success in the future of work and learning (Pellegrino & Hilton, 2012; Voogt & Roblin, 2010). However, despite its prevalence in conversation, critical thinking can be difficult to explain. Moreover, because of its ubiquity, "potential problems arise when educators are using different definitions of critical thinking, or when the banner of critical thinking is applied to nearly any topic or pedagogical activity" (Schmaltz et al., 2017, p. 1).

Critical thinking is generally thought to include the skills and dispositions for inquiry, reasoning, and problem-solving. A seminal definition of critical thinking was developed by Facione (1990) through the Delphi method that critical thinking is:

> Purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which that judgment is based. Critical thinking is essential as a tool of inquiry. As such, critical thinking is a liberating force in education and a powerful resource in one's personal and civic life. While not synonymous with good thinking, critical thinking is a pervasive and self-rectifying human phenomenon. The idea critical thinker is habitually inquisitive, well-informed, trustful of reason, open-minded, flexible, fair-minded in evaluation, honest in facing personal biases, prudent in making judgments, willing to reconsider, clear about issues, orderly in complex matters, diligent in seeking relevant information, reasonable in the selection of criteria, focused in inquiry, and persistent in seeking results which are as precise as the subject and the circumstances of inquiry permit. (p. 3)

Notably, this explanation (and many others) of critical thinking speaks to general skills and abilities, as well as dispositions—both contributing to a conception of what it means to be a critical thinker (Lai, 2011). The dispositions, attitudes, or affective components described in critical thinking are resonant of characteristics of the "ideal critical thinker." Though there is disagreement about whether both skills and dispositions are needed for effective critical thinking (Facione, 1990), they are generally seen as complimentary and have both received attention in prior literature (Ahern et al., 2019; Ennis, 1987, 1996).

The skills and abilities of critical thinking pertain to process components and the cognitive skills for developing and critiquing thoughts and ideas. Many proposed taxonomies have elaborated these critical thinking skills, see Table 1 for examples, though these are only a few. (The development of these has been interwoven as well, as McLean, 2005, integrated prior models including Brookfield, 1987, and Ennis, 1987, in the development of their model.) Though they may feel discrepant, a review of nine critical thinking frameworks showed that three main skills—analysis, evaluation, and inference—were present in each and the authors advanced these as core components of critical thinking (Li & Liu, 2021).

Table 1

Example Taxonomies to Describe Critical Thinking Skills

Components of Critical Thinking (Brookfield, 1987)	Main Cognitive Skills of Critical Thinking (Facione, 1990)	Categories of Critical Thinking Model (McLean, 2005)	Critical Thinking Abilities (Ennis, 1987, 2011)
a. identifying and challenging assumptions b. awareness of context c. imagining and exploring alternatives d. engaging in reflective skepticism	a. interpretation b. analysis c. evaluation d. inference e. explanation f. self-regulation	a. clarification of the thesis, problem, or question b. making inferences and interpretations c. supporting inferences and interpretations d. making value judgments	a. clarification b. bases for decisions c. inference d. interaction

Domain Specificity

Although traditions in critical thinking have harmonized around analysis, evaluation, and inference as skills for critical thinking, there are still questions about critical thinking in action (Dwyer et al., 2014). One of the other longstanding debates related to critical thinking is whether it is a general skill or a specific skill (Ennis, 1989; Lai, 2011). This has implications for how critical thinking would be taught—in the first case, general instruction (perhaps even separate from content instruction) could focus on critical thinking skills that are assumed to transfer to future contexts; in the latter case, content instruction would need to be infused with critical thinking application. More recent evidence has demonstrated the effectiveness of each of these approaches in improving critical thinking among their respective study participants, though studies of specific learning skills and contexts have demonstrated the greatest effect (Abrami et al., 2015; Heijltjes et al., 2014).

Still, more recently researchers have acknowledged the need for a "mixed" approach to instruction, wherein critical thinking skills can be understood through general principles as well as subject-specific criteria (Tiruneh et al., 2015). Several points support the claim for balancing the applicability of these thinking skills. First, there seem to be some skills applicable across domains, even though the problem and processes differ. Also, reciprocally, the benefit of certain critical thinking skills is dependent on understanding the domain (e.g., background knowledge) and what comprises useful thinking in that domain.

Though Ennis (1989) took issue with how to define "domain" in this sense, he conceded that this epistemological argument may resonate due to the "significant interfield differences in what constitutes a good reason" (p. 9). Epistemologically, the products of each discipline, and the ways to produce and defend those products—i.e., "how we know what we know" (Knorr-Cetina, 1999 as cited in Wilson-Lopez et al., 2020)—are discipline-specific practices. Good reasoning in a discipline entails knowing, acting, and identifying as one of the field (Dall'Alba, 2009). This begs the question then, what does critical thinking look like as applied in engineering design?

Developing Critical Thinking in Engineering Design

Cross (1982) gave an early description of the epistemological foundations of design by differentiating it from the knowledge, methods, and values of science and the humanities and identifying some “designerly ways of knowing.” The distinctive focus on the artificial, technological world and learning through “modeling, pattern-formation, synthesis” are unique approaches in design problem-solving. Compared to scientific thinking that values controlled experimentation or the arts which value analogy and metaphor, design tends to value what is “appropriate” (p. 222). Cross (1982) also described that the problems and processes and products addressed in design thinking are applicable to the “problems or issues or decisions that people are more usually faced with in everyday life” (p. 225).

Indeed, “learning to become a designer involves ‘working in a different way’ such as different ways of looking at problematic situations” (Adams et al., 2011, p. 589). Daly et al. (2012) investigated of professional designers’ sense of design. From the range of experiences described by the professionals they interviewed, they organized multiple descriptions of design which expanded from the most specific ways of acting, “evidence-based decision-making,” to “freedom.” However, based on the hierarchical organization, working with decisions was a key theme in design, no matter the level of proficiency in design. Others have similarly argued that design centers on decision-making or using best evidence and inference to improve situations (Raney & Jacoby, 2010; Salustri et al., 2009).

The centrality of decision-making and explanation in these claims about design serves well as an operationalization of critical thinking in the design process. Whether and how designers are able to effectively search, analyze, evaluate, make inference, decide, argue for, and move forward with their decisions exemplifies critical thinking in design. It is easy to recognize the multiple decision points in a design—clarifying and changing the problem, considering alternatives, and positing and testing solutions among others—which set the designer on different trajectories. Furthermore, these steps are microcosms of the larger design process to arrive at a solution which satisfies user needs. Therefore, in this work we hold that the process of making a decision or claim and supporting it with evidence and reasoning is a central way in which critical thinking emerges in engineering design work.

Evidence-based decision-making is a hallmark of effective design (Crismond & Adams, 2012), as is argumentation—the process of making and justifying claims (Wilson-Lopez et al., 2020). These skills are also important to help students prepare to produce engineering knowledge, so long as they are able to attend to what is valued in the design discipline (Sampson & Clark, 2008; Wilson-Lopez et al., 2020). Design problems provide practice with authentic contexts like those needed to learn critical thinking (Cooney et al., 2008; Jackson & Strimel, 2018). And our educational environments model professional practice wherein critical thinking will be needed to solve increasingly complicated problems (Lawson & Dorst, 2009). For instance, when students face an open-ended design they must assess where to get information about the problem and evaluate the quality of that information and its relevance for their design. Furthermore, when choosing among alternatives, the authenticity of design can support decision making and justification by empathy for real users and imagining real situations where the design could be applied. Finally, by thoughtful probing and feedback, teachers may support student growth. In sum, the design thinking practices of decisions and argumentation are through lines in design work and correspond well to general descriptions of critical thinking skills, such as analysis, evaluation, and inference. We see design learning as an important scaffold to help beginning designers learn and understand not only design thinking, but also how critical thinking is manifest in design work.

Instructional Design for Learning by Evaluating

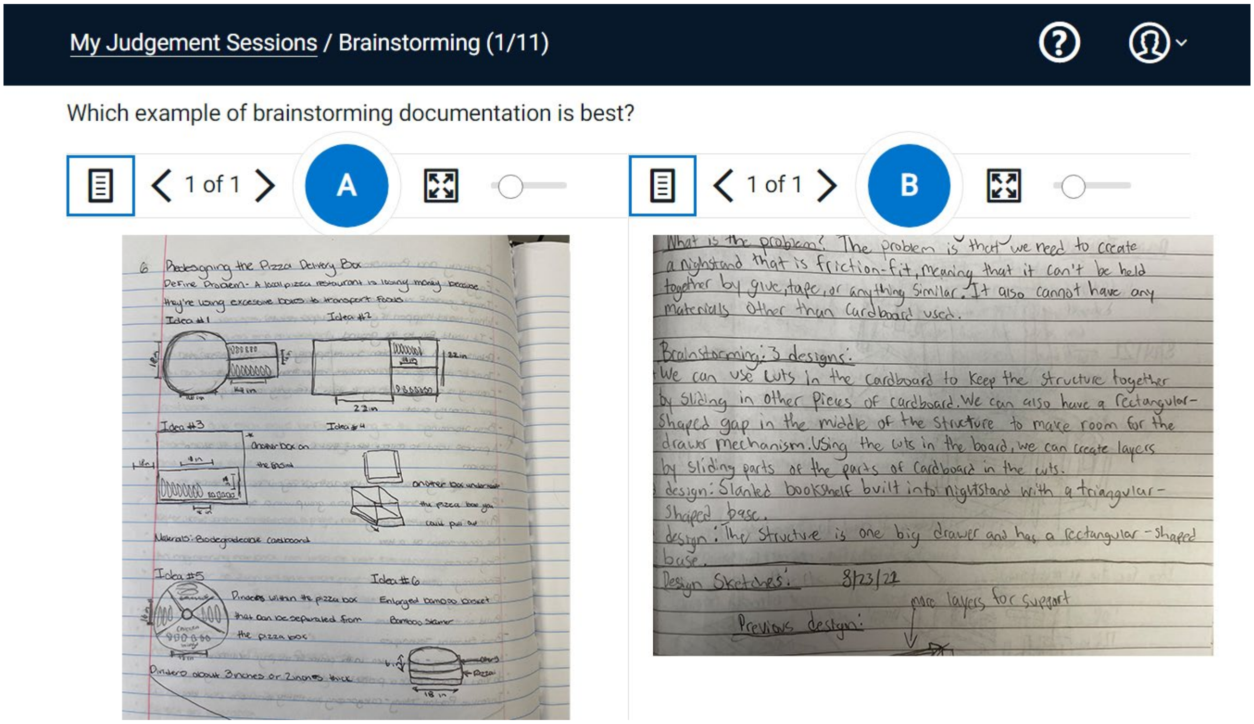
Given this demonstrated need for critical thinking, in general and in design education, our study presents the beginning developments of an instructional approach to prime critical thinking in the design process. Within the Learning by Evaluating (LbE) pedagogy we use comparative judgment to leverage some of these conceptual elements of critical thinking and focus students' decision making and reasoning. In the comparative judgment process, students are presented with sequential pairs of design artifacts and asked to explain which is better and why (see Figure 1). Furthermore, the experience takes place early in the design process, allowing the effects of these informed decisions to carry through the remainder of the students' work. Here we give an overview of the main phases of the LbE instructional approach. While a number of theoretical principles might be used to justify a given pedagogy, we offer connections we have theorized to epistemological foundations of student argumentation in engineering design (Wilson-Lopez et al., 2020) and later we examine whether these connections are demonstrated in students' judgment.

Building an LbE Experience

Preparation for an LbE comparison session corresponds to instructional design models because we recommend starting with the intended learning outcomes or key concepts you wish to reinforce through the experience (e.g., Dick et al., 2015; Fink, 2003; Wiggins & McTighe, 2005). These learning goals may correspond with the timeline for delivering instruction and the lesson wherein the LbE procedure will be integrated. We have also identified these in partnership

Figure 1

Example LbE Comparison Interface



Note. The comparison interface for making judgments. The holistic statement is indicated and students choose between option A or B. Once a choice is made, they are prompted to write an explanation. We have used software by RM Compare (https://compare.rm.com) but other alternatives may permit the same learning outcomes.

with teacher-practitioners by reviewing student work and identifying weaknesses in their design performance.

Next, once the learning outcomes have been identified, potential evaluative statements for the comparison session are made. In comparative judgment literature, this *holistic statement* serves as the predetermined criteria whereby comparisons will be made. The holistic statement should be open-ended and we have found that it is most effective when exploring qualitatively different values of design rather than a right-wrong answer. For example, criterion we would recommend include, “Which is more attractive?” “Which is safer?” “Which is a better range of ideas?” or “Which most clearly communicates the idea?”

Finally, the set of artifacts that students will evaluate must be collected. When the catalyst for an LbE session was weaknesses in student past performance, these examples may serve as a useful set of artifacts. Indeed, comparative judgment has been used in past studies to generate feedback on student work (Scott R. Bartholomew et al., 2019), though that is not the case here since the evidence is from a completed project. When thinking about alternative artifacts to present to students we have considered the "space" of the key concepts, or relevant ranges that students might be exposed to which would highlight key values in design. Part of our overall aim has been to explore whether it is necessary to include both high- and low-quality examples, though it seems that participation in any experience of comparison is fruitful (Bartholomew & Yauney, 2022).

Classroom Implementation

We have recently described three phases of the pedagogical experience of LbE elsewhere (Bartholomew, Mentzer, & Jackson, 2022), which we summarized here. In class, instruction should (a) oriented students to the experience, (b) engage them in making comparisons, and (c) build consensus and understanding through a debrief discussion.

Before beginning the comparison experience, the teacher should introduce the design context; this experience may even be proceeded by or in tandem with the beginning phases of design such as identifying the problem. As students begin thinking about the design context, the teacher may display a sample of two artifacts to model making a comparison and the associated design judgment about which artifact is better. This type of preparation may work as a method for apprenticeship in design thinking (Collins et al., 1987). We have positioned LbE at the beginning of the design experience as a primer, however this means that students may not have sufficient abilities to make comparisons or extract insights without the necessary background knowledge. Yet, these first steps may begin to activate their thinking and set expectations for the scrutiny which making comparisons will require.

Then, students proceed with making several of their own comparisons among the pairs of artifacts that are presented. The decision of which artifact is better here is based on the holistic statement determined earlier. By random selection, the artifacts shown to students may be of varying quality, including comparable quality, requiring students to discriminate on the basis of competing values or features of the idea and exposing them to the importance of trade-offs in design. Once an alternative is selected, students are prompted to write a justification of their decision using evidence and reasoning, which is their elicited critical thinking about the design artifacts. Each comparison in this phase is an opportunity for students to detect differences in design quality and over the course of several comparisons (and reinforced in the discussion held next) they may come to detect design common themes related to values in design—what matters and why.

Following individual comparison making, class-wide discussion will serve as a platform to build consensus and understanding. Individuals may think through verbalizing and internalizing key elements of the designs they have observed. By discourse and further argumentation at the class level, students may also be persuaded by others about what matters in the design and why. Question to elicit these claims and justifications in the debrief may address conceptual understanding—“Why is this important? Why does it help when designing?”—as well as technical application of the concepts—“What makes a good sketch?”—and transfer—“Based on what you saw, how will you approach the next design project?” This discourse is a further opportunity for students to gain insight about thinking and reasoning as a designer, or for teachers to emphasize certain aspects of the project and correct misconceptions. However, in our view these conversations are most effective when they emphasize the various aspects of effective design work and point out that there is not necessarily a right or wrong answer.

Theoretical Basis

While these pedagogical approaches have a certain pragmatism (i.e., what will work in the classroom), we also see ways that these steps are substantiated by theory, which we describe here. The general development of the LbE approach was based on our past professional practice, while attending to the needs and logistics of our partner teachers. Yet, the overall aims of the LbE experience are to augment students' design thinking and critical thinking, and their design performance (which we anticipate leverages these earlier cognitive skills). With the emphasis on critical thinking in design—which we earlier operationalized as evidence-based decision making and argumentation—it is appropriate to rely on the epistemological foundations of argumentation described by Wilson-Lopez et al. (2020) to endorse this approach.

In their research, Wilson-Lopez et al. (2020) conducted a systematic review of evidence of engineering arguments and argumentation. If *arguments* are products or explanations created to make and justify claims, *argumentation* is the process to create these items (Sampson & Clark, 2008). Their final selection of reviewed articles included 117 studies wherein learners had justified claims related to design. Important here for the theoretical corroboration of our approach, one research question focused on the pedagogical activities described in prior work to support argument formation, like those we have just described. Their findings describe three main epistemic practices used to support argumentation—literacy, oral language, and physical—along with 14 codes for more specific activities in each area. Although we contend that not all of these practices need to be seen in each instructional circumstance, the LbE experience was built to support students' critical thinking and several main aspects of the experience echo these codes (indicated in italics along with the epistemic practice).

Scenario (Literacy)

LbE is intended for design-based learning experiences, immersing students in a situated problem (Jackson & Strimel, 2018; Strimel, 2014). By emulating the real world, students learning while designing have the chance to imagine their work taking effect and can make more informed decisions and inference based on these thoughts. By connecting with this broader design experience, the LbE approach orients students towards the design brief or scenario they are designing for.

Differing texts (Literacy) and Observation (Physical)

When approaching the comparisons, learners see multiple viewpoints or approaches to the problem and are able to observe. When the "differing texts" of LbE—the contrasting examples in each comparison—are presented for a decision, students are more likely to recognize key features of the design that do or do not work (Loibl & Leuders, 2019). Evidence of using multiple examples for instruction also suggests that it may foster students divergent thinking (Hendry & Tomitsch, 2013), giving them a greater repertoire of ideas and evidence with which to make arguments.

Role play (Oral)

The oral literacy practice of role play encourages learners to adopt new perspectives on the problem in debate or discussion. Though it is informal in the LbE experience—most likely students mental perspective taking, though these stances may come up in the discussion—the comparison of ideas and imagination of what might work in the design helps students to be empathetic to end user or other stakeholder perspectives when making their arguments.

Engineering-related claims are constructed through social interactions, diverse perspectives, listening, and understanding (Wilson-Lopez et al., 2020, p. 294).

Whole-class discussion (Oral)

Finally, in the conclusion of the LbE approach, students exchange information as a class. Such conversations are needed to calibrate expectations (Hendry et al., 2012) and synthesize understanding of the process before proceeding. Related to argumentation, they may also operate as a proving ground for students' arguments, to see which claims and reasoning are held in common by the class or persuasive.

Though not mentioned among the epistemic practices for engineering argumentation, specifically, the LbE experience also permits students to bring forward their cultural values and past experiences as a driver for what matters in the design. In this way, students' cultural identities can be blended with the professional identities of design. Wilson-Lopez et al. (2020) acknowledged that these sources of background knowledge can be integrated with design for meaningful knowledge construction. Using cultural competence to build on students' funds of knowledge is also a central practice of inclusive education (Ladson-Billings, 1995) and indicator of good instruction.

Taken together, the approach for LbE is unique and has strong theoretical backing for its potential to support student critical thinking. The experience of LbE can be tailored to help students understand particular design values or to support deficiency in design performance. When implemented in the classroom, students have multiple chances to gain insight into the design problem, including from teacher modeling, a series of individual comparisons, or the class-wide synthesis where peers may share their thinking in new ways. Critically, the timing of these insights, with respect to the broader design process they are nested in, differs from typical approaches to feedback and evaluation in design. Because the comparative experience is at the beginning of the process, students may be more prepared to begin their design work independently. We are therefore gathering empirical evidence to inform pedagogical refinement, ensure the effectiveness of the LbE approach, and build understanding of beginning designers critical thinking.

Methods

The purpose of this research was to examine the critical thinking of beginning designers through their decision justifications in the LbE comparative activity at the beginning of the design process. Students' argumentation—how they develop claims and reasoning—and the context of their claims and reasoning itself offer fundamental insight into how students approach and reason about decisions in the design process. Thus, the research question guiding this study was, "What is the content of students' arguments when justifying decisions early in the design process?" Student explanations of their decisions were collected in the context of the LbE approach just described, and we examined them in to address research question.

Participants and Critical Thinking Evidence

Seven teachers in a large, urban school district participated in the project with their classes. Each teacher was given training on the LbE approach, including the software used to make decisions and capture student comments during the process. Teachers were also given example materials for comparison experiences and support to design their own comparison experience if it might fit their learning aims or design context better than the researcher curated examples. Following teacher professional development, comparative sessions were administered throughout the year within the Foundations of Technology (also called Foundations of Engineering) introductory course. Although each teacher was delivering the same course, their approaches and design projects did differ and 27 different types of sessions were used in the 32 total LbE sessions that were conducted in the course of the year.

Evidence of students' critical thinking was the decision justifications made in the LbE experience: once students were shown the pair of examples and had selected which they thought was better based on the holistic statement, their written explanation was collected before proceeding with the next comparison. Across all classes, 411 students made comments in the course of the LbE experience, making about 16.7 comparisons on average or 7.6 per session. Collected comments were screened for study consent and deidentified for qualitative analysis. Based on student and parent permission to participate in the research study, we were able to examine data from 83 students (20.2%) who made comments, meaning 1,578 comments (23.0% of the total comments captured) made by a mixture of students. Given the potential for participants' individual backgrounds to intersect with their engineering interests or the cultural capital they bring to the design process (Pawley, 2017), we note that of those reporting gender, 62.5% were male, 37.5% were female, and of those reporting race, 50% were Black or African American. Though we had limited participants across each class, and not all demographic data were reported, these participant demographics tended to correspond to overall classes based on our knowledge.

Qualitative Content Analysis

To explore the nature of critical thinking for these students, we applied qualitative content analysis to code and consolidate data from the diverse comments into several themes. Using qualitative methods here is appropriate given out interest in understanding students' experience and thinking, which are difficult to observe and measure (Creswell & Poth, 2018). Content analysis pertains to analysis of media—commonly text or other communication—

through themes. Content analysis has both positivist and interpretivist traditions (Kuckartz, 2014), depending on the clarity of fact or interpretation required of the content under investigation. Still, across these traditions the steps to complete content analysis generally follow (a) determining which categories/codes to use (either inductively, deductively, or a mixture), (b) applying codes to the data, and (c) looking at relationships among the codes and underlying data to identify themes.

Codes for this study were prefigured before data analysis, based on two prior studies about the nature of student explanations. In addition to the construction of arguments used to substantiate the lesson approach, Wilson-Lopez et al. (2020) also described the content of arguments seen in prior research on argumentation. Next, we used codes from Scott Ronald Bartholomew et al. (2019), who had examined the foci of judgement statements made in comparison sessions using the same platform as the LbE experience. In their study, the judges were instructors conducting evaluations of student work (compared to the students themselves evaluating example work in our study), yet the teachers' professional judgment and breadth in the comments that were captured parallels our interests in understanding the range of student arguments.

The list of items from each prior study was consolidated to remove overlapping concepts and some items deemed to not be applicable in the LbE context. Though, in doing so, some terms form one original source were elaborated in the process—for example, "human users" from Wilson-Lopez et al. (2020) was disaggregated to separate components of the original definition, which were also terms in the work of Scott Ronald Bartholomew et al. (2019). The complete set of codes and their source are noted in Appendix A. In designing the coding scheme, rather than distinguish between the various subcomponents of arguments used in prior studies, we combined these to focus on the content of students' explanations in our analysis for several reasons. Others have parsed a wider range of argument subcomponents—e.g., data, warrants, backings, qualifiers, and rebuttals (Toulmin, 2003); claims, evidence, reasoning (McNeill & Krajcik, 2008); or proposed explanations, planned tests, predictions, and conclusions (Lawson, 2003). However, more specific "sub-elements of arguments are often difficult to tease apart in analysis" (Wilson-Lopez et al., 2020, p. 286) and many frameworks to analyze arguments have avoided this difficulty by simplifying the ways in which the argument is analyzed (Sampson & Clark, 2008). Furthermore, Wilson-Lopez et al. (2020) had reduced these to two subcomponents (claims and justifications), yet Scott Ronald Bartholomew et al. (2019) did not distinguish between components of the argument, so it was reasonable to subsume these code types in our analysis. Finally, the structured approach to LbE created an implied claim (which item was better than the other), which was not always stated in the written comments. And the comments made were not often substantive enough to differentiate between these components of arguments.

Using this set of codes, student justifications were labeled with as many explanations as were given. Based on cursory reviews of data during professional development sessions with teachers and that novices' arguments most often include only a single explanation (Sandoval & Millwood, 2005), we expected there to be few instances that more than one code was applied. Consensus by the research team was used to iteratively expand the set of codes for cases that all of the existing codes were not appropriate (Kuckartz, 2014), and when the content of students' arguments was unspecified or unclear no code was applied.

Results

A cursory review of students' comments showed that in many cases, the comments between each comparison were copy and pasted, leading to duplicated and inauthentic data. We can speculate about a number of plausible reasons students may give for not participating fully in the comparisons. However, in almost all of these cases this would seem to be an indication of little critical thought when completing the activity. We reluctantly removed 251 repeated comments (15.9%), and noted this point as an opportunity for further instruction in the orientation phase of each LbE session.

Proceeding through the comments also revealed a small proportion that were unable to be coded. In some cases this was due to insufficient detail in the comments so that the research team was not able to attribute the evaluation to certain justifications in the taxonomy (e.g., “good” or “better”). Other cases revealed another avoidance tactic where students entered gibberish to avoid completing the activity. These entries signal that improved communication about the purpose of the comparisons, and how they can support student success on the next project, is necessary to engage students more fully. Still, in other cases, it is possible that the limited glimpse of our analysis was not able to capture the comparison context sufficiently that we could identify students’ rationales. Considerations of the two items being compared might clarify the explanation student offer (i.e., do the comments make better sense if we were to know the two artifacts being compared?). Furthermore, short- and long-term development in the comparisons may shed light on the reasoning provided. Despite the holistic statement and comparison being made between a pair of items, as student see more items in a given LbE session it is possible that their views are calibrated, resulting in missing context from future the written comments. An intriguing follow-up to this point would be to examine whether students’ comments become more elaborate over time, which is among our prospects for further study.

Within a sample of about 50% of the comments, the most frequent code applied in the data are displayed in Table 2. The most frequent code applied was “Aesthetic” by a wide margin.

These comments were associated with the look and feel of the design, sometimes overlapping with “Communication” or “Consumer.” For example, one comment was coded as “Aesthetic” and “Communication” because of the elaboration on the information presented in the example (i.e., “showing the product”) along with color and look: “*I prefer this because it shows the product. It also has the traditional colors…and I prefer the standard look over the other.*”

Table 2

Most Frequently Applied Codes (Based on 50% Sample)

Code	Frequency (Proportion)
Aesthetic	263 (19.8%)
Communication	72 (5.4%)
Usability	71 (5.4%)
Design	41 (3.1%)
Originality	24 (1.8%)
Consumer	24 (1.8%)
Practical	22 (1.7%)
Economics	15 (1.1%)
Organization	14 (1.1%)
Analogy	13 (1.0%)

Codes for “Communication” often referred to the level of detail that was present in the artifacts and that the details and overall ideas were understandable. There was a middle ground on the level of communication, so that designs with “*More detail [were] easy to understand*” but too much detail was a risk to other features of the artifact: “*This has both sketches and information, however both are done poorly which makes both aspects not usable.*”

Comments on “Usability” reflected a range of desirous functionality of ideas that students observed in the examples and believed would apply to their project. For example, one comparison session was related to a backpack re-design challenge and the artifacts included were various carrying devices, including some items to provoke abstract thinking. Many students commented on the comfort, pockets, space and weight, and general ease of use needed in such a project based on what they had seen. One student summarized this view in their justification about which was better by saying, "*Lot of stuff. A good backpack has to be spacious and pack tons of features.*"

When examined thematically, the codes and their frequency of use seem to correspond to several key messages which shed light on the evidence and reasoning available to these beginning designers. First, visible features of the design artifacts were the most highlighted in student comments. Obviously, their reflection on aesthetic and function of the designs would be expected, however the prevalence of these codes in comparison to other codes is notable. Further on the list are codes such as "originality" that would necessitate not only comparison between the pair, but some broader reflection about whether the design was truly novel. Other types of inference were less common, such as speculation about others' point of view (i.e., in the "Consumer" or "Economics" codes dealing with whether the designs would be marketable). The extended thinking required to make such judgments may have been a barrier for beginning designers. It is also possible that these "visible" codes represent language that is accessible for beginning designers, still learning professional ways of thinking. Conversations about aesthetic, interpretability, or usefulness of a design fall under both designers' views (for which students are being inculcated) and users' views (which students are familiar with as everyday users of technological systems).

Another notable theme which emerged was that the design contexts, holistic statements, and sets of artifacts appeared to direct students' attention and critical thinking to various types of evidence and justifications. There appeared to be clusters of similar arguments within the sessions. For example, in the backpack session just described, many comments related to usability. In a comparison session related to graphic design, students' attention was turned toward aesthetic. The few examples where "Scientific Principles" emerged all related to aerodynamics in a CO_2 car project. And the examples of "Ethics" all seemed to stem from a singular controversial image that was included in one comparison session. It is appropriate for each design situation to reflect different needs and values. The alignment that was demonstrated between students' critical thinking and these contexts though, suggests care is needed when determining the design challenges we use in class, when preparing for an LbE session, and when orienting students' critical thinking. If we wish our students to see underlying aspects of the design which are salient, we would do well to point them out.

Conclusions

Critical thinking is an important cognitive ability. Design requires the ability to evaluate and integrate knowledge from various disciplines and sources—scientific principles, users, testing, and our own intuition. The design process also contains many opportunities for decision-making, meaning that as student move forward, they have multiple opportunities to exercise their critical thinking and reasoning. The LbE instructional approach described in this paper represents a keen opportunity to expand students' critical thinking in design by the structure of modeling, comparing, and discussing what matters in design and why. Furthermore, as we described in this paper, it is a theoretically sound approach to support the epistemic practices of engineering-related argumentation.

We are continuing to build an empirical case for the LbE experience, including this examination of student's critical thinking. Herein we have described codes for critical thinking and argumentation in design to illustrate how student make and justify their decisions. In general for these beginning designers, attention was paid to the most visible aspects of the design. However, there are strong patterns related to the design context, which presents an opportunity for further study of design and critical thinking, as well as specific insights to tailor the LbE approach.

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Appendix A. Coding Scheme

The coding scheme was developed by integrating terms from Wilson-Lopez et al. (2020) and Scott Ronald Bartholomew et al. (2019). Indicated below are the codes used in this study which we believe are more comprehensive and remain generalizable to design argumentation. In the source column, lead author initials (W or B) indicate the original source of the term, with an asterisk where the ideas were represented similarly or adapted from the original.

Code	Definition – What is used to justify the claim?	Source
Aesthetics	Comments about how aesthetically pleasing the design of the artifact was	B, W*
Analogy	Comments or explanations based on previous cases or experience	W
Authority	Comments invoking expertise from a text or person to justify the claim	W
Brainstorming	Selection based on strategies for brainstorming in the artifact	B
Communication	Comments on how clear the work/idea was, or how understandable it was	B
Completeness	Comments about how complete, or thought through the design seemed to be	B*
Complexity	Comments about how complex the work/idea was	B
Construction	Comments about the quality of the artifact construction, e.g., durability	B
Consumer	Explanation based on an appeal to the consumer, user, or audience of the work/idea	B, W*
Data	Using empirical test results or observations to justify a claim	W
Design	A general argument related to the overall design or perceived potential of the work/idea	B, W
Design process	Argument addresses how well the work/idea followed the design process	B
Economics	Explanations based on budget, economic impacts, or revenue (or other similar terms)	W
Environment	Comments based on projected or actual environmental impacts, e.g., damage or sustainability	W
Ethics	Comments appealing to values, moral judgments, or articulations of right and wrong	W
Evaluation	Argument that the artifact does or does not meet a constraint or criteria for product quality	B*, W

Failure analysis	Argument or explanation based on process, product, or system failure	B*, W
Labels	Comments addressing how clearly the artifact was labeled	B
Neatness	Comments about how neat or clean the work seemed to be	B
Organization	Explanation about how organized the work/idea was	B
Originality	Comments about how unique, creative, or innovative the work/idea was	B*, W
Practical	Comments about how practical or workable the design is	B
Problem id	References to a clear problem identification in the artifact	B
Realistic	Comments about the realism of the artifact	B
Regulations	References to law, ordinances, policies, or standards that guided the selection (outside documents to the class)	W
Safety	Factors related to human safety or health or arguments based on responsibility for oversite, consequences, or risks of the idea	W*
Scientific principles	Comments using scientific or mathematical concepts to explain the artifact	W
Testing	Comments based about testing design, quality, or variables used	W
Usability	Comments about how usable or user friendly the product seemed to be or that it offered good functionality	B