The 107th Mississippi Valley Technology Teacher Education Conference
Nashville, Tennessee

Session VI: MVTTEC-Related Research

Critical Reflective Writing in Technology and Engineering Design-based Learning

November 19, 2021

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Abstract

Critical incidents cause "high impact" reflection in learners, and reflection has been correlated with successful design thinking (DT) in technology and engineering design-based learning (T/E DBL). However, a framework for integrating critical reflection into design-based learning (DBL) does not exist, and researchers know little about students' reflections during its iterative, decision making phases where critical reflection might count. For example, it is possible scaffolding critical reflection during ideation and prototyping could help students review their intrapersonal frameworks more often, slowing decision making and improving abduction. Since writing is a reflective tool and slows thinking, critical reflective writing might be a way to slow and concretize students' reactions to critical incidents, impacting agency, identity, and perseverance. Borrowing from the scholarship of rhetoric and composition theory (CT) that has instrumented writing to learn (WTL), this research relates critical reflective writing to learn (CRWTL) to T/E DBL. The current paper constructs a justification for using a flexible framework for integrating CRWTL into the iterative phases of DBL. Toward the end, it explains exigences for reflection and clarifies ways to think about the timing and impetus for CRWTL. Then, a simple thematic outline prefigures alternative ways to think about bounding T/E DBL, so future research can interpret patterns of critical reflection. Also, this emergent construct informs ways one can survey learners to see if CRWTL impacts their T/E DBL during iterative prototyping differently from an untreated population. Overall, this paper expands knowledge about reflection and DT, so T/E can help less-expert engineers close the gaps with more-expert engineers. Results from this study could also shape an imagination for how DT crosscuts education, curriculum, and instruction for lifelong learning.

Keywords

Composition Theory, Critical Reflection, Critical Reflective Writing, Design-based Learning, Design Thinking, Engineering, Prototyping to Learn, Rhetoric, Technology, Transformative Learning, Writing for Transfer, Writing in the Disciplines, Writing to Learn.

Critical Reflective Writing in Technology and Engineering Design-Based Learning

Design thinking (DT) activates authentically situated, practical, and embodied learning in several disciplines at once, and it is "*a model of thinking* that is important for every student to develop and have in the twenty-first century" (Li et al., 2019, p. 101). Being broadly integrative, DT has instigated interdisciplinary teaching and learning throughout education, especially in

STEM. In technology and engineering education (T/E), the adaptation of DT has been a trend for one hundred years, spurred by innovative technologies in information, communication, and computation and shaped by research in education, learning, and social-behavioral sciences (Froyd, Wankat, & Smith, 2012). DT has also cross-pollinated technology and engineering education (T/E) with disciplines outside of STEM, such as writing and rhetoric, health and medicine, business management, and organizational development, and this cross-pollination has also led to innovative interdisciplinary research.

This interdisciplinary research has led to a plethora of acronyms that variously integrate science, technology, engineering, and math, to include STEM (science, technology, engineering, and math); STEAM (science, technology, engineering, art, and math); STEAMM (science, technology, engineering, art, math, and music); and STEL (science, technology, and engineering literacy), and the list goes on. Influenced by the scholarship of teaching and learning (SoTL) and DT (Cross, 1982, 1989, 2011; Huber & Hutchings, 2004, 2005; Huber Hutchings, and Ciccone, 2011; Schön, 1983, 1987, 1995), programs in T/E have emerged, reconceiving STEM-rich DT as integrative technology and engineering design-based learning (T/E DBL). One example is the integrative science, technology, engineering, and math education (I-STEM Ed.) program at Virginia Tech, which has established a flexible model for intentional, hands on, design-based teaching and learning, K-18 (Sanders, 2009, 2012; Wells, 2012, 2013, 2016; Wells & Ernst, 2012/2015).

These acronyms have emerged from shared attempts to symbolize complex, cross-cutting T/E learning systems invoked by students when they uniquely engage with authentic, hands on problem solving. These acronyms also signify challenges educators face when they must continually re-imagine adaptive cross-disciplinary curricula apt for authentic, localized teaching and learning. These integrative curricula have micro- and macro-constituents. While a granular focus in DBL can be uniquely and materially centered on knowledge, problems, and solutions, a macro-view of critical DT operating throughout DBL suggests complex, non-linear intrapersonal reflection interweaves these hands on activities, and this reflection supports broader critical thinking.

Understanding how to scaffold critical thinking when it has been made invisible in DT scholarship has been a challenge compounded by the complex nature of 21st Century instructional design (Doll, 1998, 2010). The research has assumed DT catalyzes cross-cutting reflection and promotes learners’ STEM literacy. However, understanding how to relate DBL and hands on prototyping with the genesis and practice of reflection and critical thinking is important. While J. Mezirow (1990; 1997) and other educators have correlated critical reflection and metacognition with transformative lifelong learning, T/E has not yet established an agenda for describing learners’ critically reflective performances. However, researchers, such as Moloney et al. (2016) and Moloney, Badenhorst, & Rosales (2018), have emphasized that understanding reflective thinking is important for developing long term engineering competencies.

It is surprising that while SoTL has consistently advocated for authentic, integrative hands on experiential learning because of its perceived benefits for higher level critical thinking, it has not construed a unified, interdisciplinary framework for scaffolding intrapersonal critical reflective thinking related to advanced metacognition. It is equally surprising, given the implied relationship between DT and reflection, that T/E has not deeply described design-based reflection and critical reflection in T/E DBL. These omissions have resulted in leaving the intrapersonal realm of reflection defined as *tacit*—for novices and experts alike.

However, research has emerged in the scholarship of rhetoric and writing that uses writing to improve metacognition, such as writing for transfer (WFT) and writing across the curriculum (WAC). Writing to learn (WTL) is an offshoot. This paper's research emphasizes the crosscutting, reflective value of writing significant for T/E DBL, and it explores ways WTL could enhance critical reflection and meta-awareness in DBL. This kind of writing is defined in this paper as critical reflective writing to learn (CRWTL), distinguishing it from other ways to write with varying degrees of reflection.

Scaffolding CRWTL might be useful for concretizing designers' reflective DT, and could strengthen DBL, especially where students contend with complex, open-ended design-based problem solving and high stakes writing in the discipline (WID). As educators throughout higher education strive to improve critical thinking by instituting WAC (Anderson, et al., 2015; 2016; Anson, 2015; Anson & Moore, 2017), T/E has skin in the game, because CRWTL and T/E DBL might go hand in hand to promote deeper, lifelong learning.

Individualistic Learning: Gaps in Awareness and Understanding

Micheli et al. (2019) have provided substantial groundwork in their systematic literature review for describing DT. In their conclusion, they emphasized that even though DT is highly collaborative, leaders in product development and business management need to prioritize professional development that improves individualistic DT.

In theory, DBL foots that bill. It prepares learners of all ages to tackle real world problems through integrative, hands on prototyping. Authentic, real world problems engage critically transformative, individualistic experiential learning (Gomez Puente, van Eijck, & Jochems, 2011, 2013, 2015; Kolb, 2014; Mezirow, 1990, 1997; Moon, 2004), through authentic, hands on encounters with STEM and other "threshold concepts" (Meyer & Land, 2006a; Meyer & Land, 2006b; Vygotsky, 1978, 1934/2012). It is important to note that when learners engage with threshold concepts, they experience critical reflection often correlated with successful long term transfer (Bransford, Brown, & Cocking, 2000; Perkins, 2006; Perkins & Salomon, 1992). That is, as learners design to learn in liminal places (Meyer & Land, 2006, pp. 375-376; Vygotsky, 1978, 1934/2012) filled with complexity and uncertainty, they reshape and advance their intrapersonal content knowledge, language, and hands on practical awareness (Land, Rattray, & Vivian, 2014; Meyer & Land, 2003, 2005; Vygotsky, 1978, 1934/2012).

Unfortunately, individualistic integration like this cannot happen unless learners *recognize* the significance of their learning and connect it to their own lives in meaningful ways (McCarthy, 1930/1949; Vygotsky, 1978, 1934/2012; Wood, Bruner, & Ross, 1976). While it has not been deeply described in T/E, SoTL has indicated scaffolding for authentic, experience-driven instruction engages learners and helps them realize ways to learn for themselves (Bransford, Brown, & Cocking, 2000; Huber & Hutchings, 2004). Some T/E research also concludes DT and DBL trigger recognition, knowledge, reflection, and critical reflection (Moon, 2004, 2006, 2010, 2016) and the research also implies T/E DBL contributes a metacognitive advantage for learners when they confront future complex, open-ended problems, and conceptual difficulties later (Bransford, Brown, & Cocking, 2000; Efklides, 2006). However, this cannot happen without complex scaffolding.

T/E DBL

Since its inception, balancing complex intra-, inter-, and trans-disciplinary content essential for scaffolding DBL has been a challenging work-in-progress (Richter & Allert, 2017). These challenges make it difficult to describe and assess DBL on an individual level, yet it is necessary for researchers to understand learners' design-based performances and transformative STEM-integrative learning before educators can legitimately support DBL in their fields (Ge & Liefer, 2020; Li, 2018; Li et al., 2019).

Ostensibly, DBL fulfills all engineering criteria that equally parse learners' cross-disciplinary learning with their standardized, intra-disciplinary and inter-disciplinary STEM learning (ABET, 2020; ITEEA, 2020). By targeting higher order thinking skills along with traditional STEM content and procedural knowledge, DBL strikes a balance between what is professionally pragmatic for technology and engineering students and what is epistemic for all learners, a win-win, because DBL institutes T/E learning by doing.

For example, Kim et al. (2019) have shown that when engineering students learn to critically reflect during their design processes, they engage with the philosophy, rhetoric, and ethics holistically related to their designs. This causes them to recognize DT has broader consequences, beyond the situation at hand. Critically reflecting on these impacts helps learners make empathic and intentional choices, while they are learning to be practical, flexible, and ethical practitioners for life (Kim et al., 2019). However, little empirical work in this intrapersonal realm informs best practices (Hess & Fore, 2017), and the recent research makes it clear that facilitating changes in learners' deep, intrapersonal schema needs sensitive support and coaching (Ge & Liefer, 2020).

Per the constructivist model, DBL is collaborative, and it invites less-expert learners to become more expert through the intentional scaffolding of complex activities that advance novices' language and practice alongside more expert individuals while they are designing to learn. In the process, novices learn what they might not have learned without that expert assistance. DBL perpetuates learning in ways lecture-based and apprentice-based pedagogies do not, allowing learners to become "experts" in ways that fortify their self-identification in the field. This is due in part to the parity between less experienced learners and more expert people in the DBL classroom (Stone, 1993), a parity intended to build learners' agency and identity by sharing content-rich language and practices alongside those more expert people, such as their instructors.

However, troubling experiences unfold in T/E DBL, as less-expert learners learn to question and research freely with more-expert people. While it seems to be an ideal epistemology, instructors need a firmer foundation to facilitate critically reflective, hands on problem-solving agility and agency, so students can learn to adapt and persevere in complex settings where new problems are complicated, expertise is often variable, and solutions are unclear (Land, Rattray, & Vivian, 2014).

Research has examined impacts for DBL in high school engineering education, but less research exists in higher education (Gomez Puente, van Eijck, & Jochems, 2011, 2015). However, this research has uncovered aspects of DBL's theoretical and conceptual frameworks that might be useful throughout education (Gomez Puente, van Eijck, and Jochems, 2011, 2015). However, the higher order thinking skills associated with active learning in DBL, such as reflection, critical reflection, and metacognition, have not been described in learners' design encounters.

For example, studies appear to assume reflection happens during DBL, especially in iterative phases for prototyping, but these have not explained reflective activities and clear benchmarks for degrees of reflection (Hacker & Barak, 2017, p. 44). Studies explicitly mention reflection (Householder & Hailey, 2012), but few describe what students experience in real time that produces the degree of critical reflection necessary for successful "transfer" (Perkins & Salomon, 1992). Also, research indicates that students do not transfer DBL well into future design-based situations at all, suggesting that instructors need to provide explicit scaffolding for reflection, critical reflection, and meta-awareness consonant with threshold domain content knowledge (Bengtsson, 2012; Meyer & Land, 2006a; Ge & Leifer, 2020) about what M. de Vries (2008) has called the "physical" and "functional" attributes of the emerging artefacts and the "relationship" of the physical to the functional (de Vries, p. 31).

A Shift in Semantics and DT Perspectives

Also, a groundbreaking question might arise, "Threshold for whom? From whose perspective?" The gradual integration of DT across disciplines has led to a semantic shift from DT to DBL, and this shift impacts how researchers scaffold hands on learning. DT is a hermeneutical concept rooted in constructionism, and it emphasizes learning exchanged between an individual's DT and the artefacts he/she designs and uses, making intrapersonal, embodied learning central to design research (Cross, 1982; Fleury, Stabile, Carvalho, 2016; Haas & Witte, 2001).

In contrast, DBL is a way of teaching and learning that often blurs constructionism and social constructivism, so while DBL leverages individualistic DT, it does so for collaborative, STEM-integrative hands on learning during design, shifting the continuum from "designerly" (Cross, 1982) DT to techno-scientific, outcome-based DT (Cross, 2011; Fleury, Stabile, Carvalho, 2016). Therefore, DBL often emphasizes team participation and product development (more akin to traditional engineering which sees prototyping as an end goal) *versus* individualistic prototyping to learn engineering design (Cross, 2011).

Invisible, Intrapersonal Realms

This semantic shift has caused oversights that blur knowing learners' reflective perspectives about what is personally significant, apt, and transferable for them (Tracey &

Hutchinson, 2016). While individual reflection has been considered a linchpin for constructionism and social constructivism, somewhat blended in T/E DBL, the exigences and bounds for learners' reflective performances have not been deeply explained, and this has been confirmed throughout the literature focused on an agenda for instituting reflection (Cosgrove, Ryan, & Slattery, 2014; Cosgrove & O'Reilly, 2020; Gomez Puente, Van Eijck, & Jochems, 2011, 2013, 2015; Mina, Cowan, & Heywood, 2015; Patel & Dasgupta, 2019; Turns & Roldan, 2019; Vygotsky, 1978, 1934/2012).

Altogether, the intrapersonal reflective realm of threshold knowledge has been invisible in DBL. However, a lot of the literature correlates individual reflection and reflective activities with degrees of expertise and design success, K-18 and beyond (Atman et al., 2007; Crismond & Adams, 2012; Cross, 1982, 2011, 2018; Cunningham & Kelly, 2017; Fan, Yu, & Lou, 2018; Hong & Choi, 2019; Li, 2018; Li et al., 2019; Grubbs, Strimel, & Kim, 2018; Strimel, Grubbs, & Hoffman, 2019; Schön, 1987; Thibaut et al., 2018; Wells, 2016). In sum, this literature has not provided concrete examples of reflective performances, leaving opportunities for determining patterns for reflection during the iterative design process and understanding their impact.

A niche exists for describing and correlating reflective performances with DBL that could inform T/E DBL scaffolding. Another niche exists for studying impacts of critical reflective performances in the affective, social, cognitive, and psychomotor domains essential for engineering teaching and learning (Vanasupa, Stolk, & Herder, 2009). For example, opportunities exist for correlating intrapersonal reflection with emotion, self-efficacy, materials awareness, professional identity (Menold et al., 2018; Welsh & Dehler, 2012), which might inform best practices for T/E engagement and retention.

To conclude, much of what is believed about the mutual impact of reflection and design-related activities has been assumed and speculated for individuals, especially during the active, iterative hands on phases of engineering DBL. As a result, what learners are thinking and feeling about design challenges in DBL has been a mystery, and these blind spots interfere with efforts to scaffold learners' critically reflective performances essential for metacognition and successful learning transfer.

Filling the Gaps: "Reflect and Redesign"

Recent research has correlated reflective performances and hands on activities *throughout* the iterative phases of design in DBL, *in medias res*, and it suggests that scaffolding reflection during iterative prototyping might improve the frequency and quality of prototyping for less expert designers, such as by improving their problem definition (Deininger et al., 2017; Hong & Choi, 2019; Minnes et al., 2017) and reducing idea fixation (Hatchuel, Le Masson, & Weil, 2011). It makes sense to integrate critical reflection during the intermediate phases of design, because this is where designers deal with uncertainty and inertia (Ge & Leifer, 2020; Tracey & Hutchinson, 2016). They also struggle to juggle complex, nonlinear phases of inductive, deductive, and abductive critical thinking while also contending with latest content knowledge and interpersonal communication (Crismond & Adams, 2012; Cross, 1989, 2011; Fleury, Stabile, Carvalho, 2016).

This is also where learners are likely to grapple with myriad threshold concepts that promote transformative, transferable learning (Meyer & Land, 2003, 2005, 2006a), such as realizing a “troublesome” (Meyer & Land, 2006a, 2006b; Perkins, 2006) relationship often exists between their attitudes about uncertainty and their nascent, intrapersonal professional identities (Tracey & Hutchinson, 2016; Moloney et al., 2016; Moloney, Badenhorst, & Rosales, 2018). One recent qualitative study, borrowing from John Dewey’s theme of perplexity (Ge & Leifer, 2020), concludes that engineering design presents intrapersonal challenges that can become real obstacles, but it does not specifically investigate relationships between critical reflection, CRWTL, and the complex setbacks related to DT the study explains.

Boundaries: Timing, Audience, Genre, & Writing

Bounded by Schön’s chronological framework for creating the final prototypical artefact (1983, 1987), most foundational research in T/E DBL has used spoken protocols for explaining “reflection-in-action” during the iterative and active phases of DBL and “reflection-on-action,” timed for after the design was complete. Consequently, learners’ introspective, critically reflective performances have not been deeply investigated to understand what they think about changes in their intrapersonal frameworks for content knowledge, language, and practice—not in ways that suffice for identifying individuals’ altered competencies for long term transfer. Future research bounded by “reflection-in-action” (Schön, 1983, 1987) might reveal new themes about reflection and iterative ideation, especially during the reflect and re-design phases.

Because audiences external to designers and students of DBL have shaped much of the research, most have provided generic data, such as summative, formative, and standardized testing; institutional assessments; surveys; and design artefacts, such as prototypes, design journals, design briefs, drawings, and other WID. Even participant interviews, spoken protocols, and discourse analyses of individual and collaborative activities have been unevenly shaped by audiences external to the subjects (Cross, 2011; Schön). While recent research has studied reflective activities, this research has not integrated self-reflective writing interventions, beyond loosely defined, ongoing reflective writing mined for ideas about writing analytics pragmatic for assessing metacognition (Gibson, Kitto, & Bruza, 2016; Shum et al., 2017). Additionally, writing for the design journal, final reports, E-Portfolios, and wikis where learners retrospectively record and describe their experiences has been studied. Writing is situated and embodied (Rule, 2019), and it is reflective and epistemic (Dryer, 2015; Emig1977), because writers move from ideas to text repeatedly throughout their invention and delivery processes.

However, writers’ description, reportage, and record keeping are least reflective in learning theory (Kember et al., 2008; Summers et al., 2016). After all, designers do more than transcribe, describe, and process. Future research might be significant, if it foregrounds reflective activities that reveal more about what designers are thinking about their DT while they are designing and writing. Research that discloses to what degree reflective performances impact individual’s intrapersonal frameworks and iterative design decisions could inform better ways to scaffold T/E, and the additional integration of critical reflective writing could inform interdisciplinary frameworks already established (Passow & Passow, 2017; Navarro et al., 2016).

Generic Writing in the Discipline Is Not Enough: Critical Reflective Writing to Learn

Multidisciplinary research exists for scaffolding WID to improve engineering thinking and communication in T/E, and this research indicates WTL supports long term WID transfer (Beaufort, 2007; 2012; Ramirez-Echeverry, Dussan, and Garcia-Carillo, 2017; Irish, 1999; Jeyaraj, 2017; Staton & Rendahl, 2014). However, as an end, WTL that solely targets generic WID is not sufficient for transfer (Anson, 2015). For example, Bengtsson et al. (2012) instrumented a project plan, a constructions and calculations report, an exhibit, a prototype demonstration, a technical report, and peer reviews in their study involving a design and build electric speaker project. While the students made disciplinary learning gains, such as having an advanced awareness of complex systems in design, they did not effectively apply the theoretical and conceptual domain content knowledge necessary for a successful design. The authors concluded "…activities that helps [sic] the students reflect and analyze the outcome of the hardware designed to their theoretical model of the system should be introduced" (p. 9).

This conclusion suggests that critical reflective writing might have helped. Schoen et al. (2018) have indicated that integrating engineering WID, such as requiring case studies, can produce stress, even though it serves to raise "awareness of global issues" (p. 5), and their research suggests T/E should find other ways to integrate writing in engineering for positive affect. Hubka, Chi, & Svihla (2018) confirm this where they indicate that whether writing promotes learning to write in the discipline, or it promotes reflective WTL, it must make sense and be unobtrusive. This sentiment has been true for instructors and learners alike (Goldsmith & Willey, 2016a, 2016b; Goldsmith, Willey, & Boud, 2019).

Altogether, less research involves reflective, intrapersonal WTL, a genre commonly associated with design and writing for transfer (Thibaut et al., 2018). For example, less is known about how less-expert designers manage intermittent setbacks and design failures that challenge them to persevere. Since less has been studied about individual critical reflective behaviors in T/E, especially during the active phases of design-based problem solving, little guidance exists for scaffolding reflection and reflective writing to support inexpert learners during ideation and prototyping, even though critical reflection and critical reflective writing have been positively associated with hands on learning in other fields, such as dentistry (Bowman, 2020), fashion design (Ryan & Brough), nursing (Kim, 1999), social work (Whitaker & Reimer, 2017), and writing and rhetoric (Irvine, 2020).

While researchers have struggled to justify the integration of writing into T/E activities (Goldsmith & Willey, 2016a, 2016b; Goldsmith, Willey, & Boud, 2019), it is still believed that self-reflective practices exist, and ways of writing, including critical reflective writing, can help designers to manage DBL in transformational and transferable ways that have high impact (Summers et. al., 2016). More studies that instrument critical reflection to yield concrete data for describing exactly why individuals reflect and what they choose to reflect on during DBL might fill the gaps in the research related reflection during hands on prototyping.

So far, assumptions exist in T/E that critical reflective performances happen naturally and constructively throughout DBL. However, much DBL happens with negative affect, even anger, leaving designers lost in the "'Death Valley' of reframing" (Ge and Liefer, 2020, p. 660).

It is likely that all designers struggle with ideation and reframing throughout life, "but the ability to articulate these internalized processes provides the designer with the power to understand them [their ideation processes] and manage them with intention" (Tracey & Hutchinson, 2018, p. 283). Therefore, scaffolding critical reflection might help designers manage complex, open-ended phases of iterative, hands on problem solving.

Since clear frameworks for engaging reflective practices do not exist, it is certainly possible to borrow from writing and rhetoric conceptual frameworks regarding writing for transfer, such as WTL and WID. And more narrowly, it might be possible to design and implement critical reflective tools, such as CRWTL. Instrumenting CRWTL might impact design performance and intradisciplinary knowledge while expanding intra- and interpersonal proficiencies across contexts—for long term transfer.

In sum, with a lack of consensus about DBL's integrative merits and best integrative practices (Thibaut et al., 2018), the instrumentation for critical reflection and critical reflective writing could inform the integration writing into of T/E DBL. As it stands, few studies concretizing critical reflection and critical reflective writing exist. Since notable attrition from engineering happens, and this attrition connects to learners' affective domains, CRWTL might help in transitional places, such as first year engineering, where students strive to adjust.

Purpose

Until there is a better understanding of students' intrapersonal exigences for critical reflective performances and how critical reflective writing correlates with DBL, instructional designers cannot effectively integrate reflective activities into DBL, so heuristics related to critical reflection are not clear for DBL. This is a problem because students might perform DBL well within a particular situation, yet they might not necessarily transfer their learning into a newly situated design problem, not without advanced meta-awareness and related crosscutting critical reflective practices to guard them against these setbacks.

The purpose of this study is to describe critical reflective writing in T/E DBL during the reflect and redesign phases of T/E DBL and compare its intrapersonal impacts with an untreated population. This research will clarify theoretical definitions for reflection in DT and inform best practices for scaffolding CRWTL in T/E DBL for enhanced metacognition and transfer later.

Research Questions

RQ1. What patterns exist in CRWTL during reflect and redesign phases for DBL?
RQ2. What impact do learners perceive CRWTL has on their DBL prototyping for
- SSQ1: Idea fixation?
- SSQ2: Iteration and abduction?
- SSQ3: Problem definition/scoping?
- SSQ4: Materials awareness/affect?
- SSQ5: Engineering agency?
- SSQ6: Engineering identity?
- SSQ7: Perseverance?

RQ3. Compared to untreated populations, how does critical reflective writing impact DBL for

SSQ1: Idea fixation?
SSQ2: Iteration and abduction?
SSQ3: Problem definition/scoping?
SSQ4: Materials awareness/affect?
SSQ5: Engineering agency?
SSQ6: Engineering identity?
SSQ7: Perseverance?

Outline for Future Work

The intent for this study is to design and implement scaffolding for CRWTL in first year engineering DBL classrooms, describe emergent themes, and compare impacts of this treatment with several untreated classrooms. The outline for this mixed methods study includes:

1. Construct a framework and timing for the critical reflective writing treatment from the literature.
2. Design the critical reflective writing prompt for the treatment by understanding the exigence and impetus for critical reflection.
3. Design and implement a pre- and post-survey that reveals impacts for psychomotor, social, cognitive, and affective domains from critical reflective writing.
4. Implement the critical reflective writing intervention.
5. Describe themes that emerge from students' critical reflective writing during iterative prototyping (reflection-in-action).
6. Record students' perceptions of the impact the critical reflective writing had on their DBL performances (reflection-on-action via recorded interviews).
7. Compare impacts for critical reflective writing on psychomotor, social, cognitive, and affective domains (comparative post-survey for T/E DBL) as understood using the pre- and post-survey.

Theoretical and Conceptual Backdrop

Several theoretical frameworks guide this research. By selecting integrative, hands on DBL as a framework and critical reflective writing as the instrument for concretizing individuals' critically reflective insights, this study naturally draws from constructionism and social constructivism (Harel & Papert, 1991; Vygotsky, 1978; 1934/2012), as they relate to learning by doing. Additionally, Meyer and Land's emergent theoretical framework for "threshold concepts and troublesome knowledge" (2006) has deeply influenced the design of the critical reflective writing instrument, because this study prompts students to recognize and reflect on their own critical incidents in DBL, not those speculated or interpreted by our research team. Theories for reflection informing our interpretation of critical reflective writing and DT have been drawn from Emig (1977), Schön (1983, 1987, 1995), Moon (2006, 2010, 2013), Kember et al. (2008), Cross (1982, 2011, 2018). J. Wells (2016) and Y.-C. Hong & I. Choi (2011, p. 687; 2015; 2018, p. 340) have presented theoretical models of designers' reflective thinking which have influenced this synthesis from of classical rhetorical concepts and DBL.

Finally, understanding the relationship between complex activity systems in DBL and reflective writing has been holistically informed by rhetoric and composition theory (CT), integrative SoTL (Huber & Hutchings, 2004; Huber and Hutchings, 2005; Huber, Hutchings, and Ciccone, 2011), discourse community theory (Swales, 1988, 2014, 2020), and activity systems theory (Russell, 1997)—particularly as related to intradisciplinary and interdisciplinary ways of writing to communicate and learn, such as WID and WTL. Hacker, Keener, and Kircher (2009) have also influenced this research by defining "writing" as "applied metacognition" (p. 160), justifying our decision to use CRWTL strategies in concert with transformative DBL that engenders the critical incidents and critical reflection necessary for developing learners' long term metacognitive awareness in DBL.

Emerging Constituents and Bounds for this Research

This paper contributes granular insights into exigence which helps learners, educators, and researchers recognize what precipitates reflection, so it can be described better, and an emergent coding for these can be found in Table 1 on page 12 and Table 2 on page 15 of this paper. We also add more details related to impetus, timing, place, and degree of intrapersonal recognition and reflection in DBL activities. In sum, the conceptual framework presented next resembles the rhetorical situation, its ongoing activities, and its elements (Downs, 2020). For example, identifying exigences related to critical reflection during the iterative phases of DT informs ways to prompt students to recognize boundaries related to their reflective activities that might have been "unseen," even for them. Of particular interest, too, is bounding this research by design phases, so we can understand patterns related to cognitive performances, such as induction, deduction, and abduction during DT's iterative phases.

Table 1 beginning on p. 12 of this paper encapsulates exigences drawn from the literature, such as doubt, concern, surprise, frustration, joy, and satisfaction. These allow for insights into situational timing and bounds for critical reflection during DBL. The concept of exigence also informs ways to construct a research chronology for reflection related to the completion of the artefact, to include reflection-for-action, reflection-in-action, reflection-on-action (after the artifact is finished and communicated), and reflection-for-future-action (Moon, 2004, 2006, 2010, 2013; Schön, 1983, 1987, 1995).

Narrative point of view informs ways to think about the designer's reflective spectrum—from deeply intrapersonal to an objective, interpersonal view. Point of view also informs the learner's correlation of domain content knowledge with complex systems and subsystems awareness. This includes individual ethical and moral frameworks, as well as the learner's degree of empathic awareness for audience/client while understanding design constraints.

Finally, the phases for DBL loosely correlate with the five canons for "composition and inscription" (Downs, 2020, p. 477), as shown in Figure 1 p. 14 of this paper. Thus exigence, invention, arrangement, style, memory, and delivery parallel terms in T/E DBL. These include identify problem/need; define problem and constraints; research; ideate; prototype; reflect, research, and re-design; finalize solution; realize solution prototype; communicate solution. These activities are not linear in either rhetoric and composition or DBL (Atman et al., 2007; Wells, 2016), making them likely to erupt at any time during DT, as learners recognize and reflect during its iterative divergent and convergent phases of induction, deduction, and abduction.

These activities may be related to taxonomies, such as the well-known Bloom's Taxonomy for Critical thinking, but these are not to be construed compartmentally or hierarchically. Figure 1 on p. 14 in this paper demonstrates this T/E DBL process. In the affective realm, critical reflection and critical reflective writing might influence problem definition and framing, design fixation, perseverance, iterative and abductive reasoning, professional identity, self-efficacy with materials, and wider systems of knowledge and practice related to ethics important for imagining unforeseen consequences for the design.

Table 1

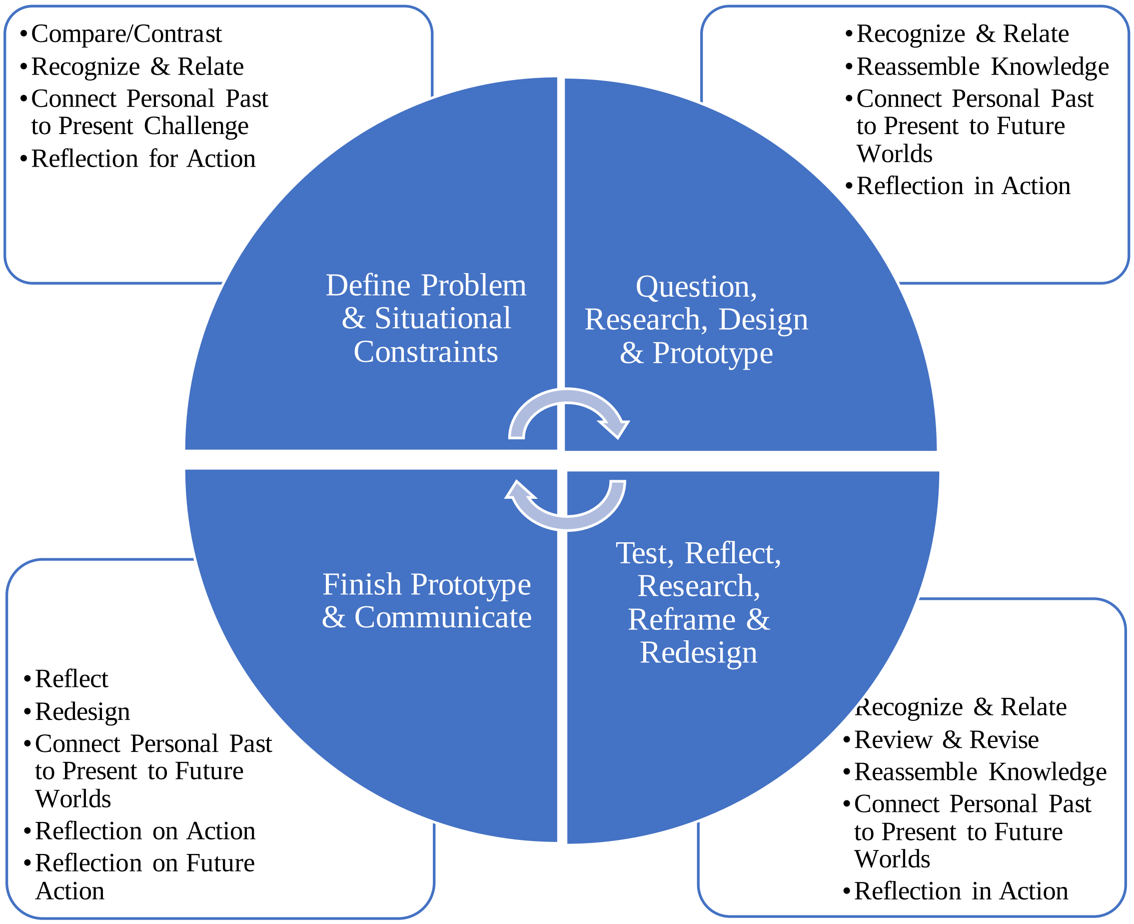
Themes for Exigence Useful for Prompting CRWTL

Research	Field	Themes
Adams, Turns, & Atman (2003)	Engineering Teaching & Learning	"Surprise that stimulates reflection in such a way as to influence action," (p. 286), unpredictability, talk back, joy
Adler-Kassner et al. (2018)	Composition & Rhetoric	Need to communicate
Aleong, Joslyn, & Adams (2018)	Engineering & Design	Surprise and doubt in the face of complex uncertainty
Chateauvert (2017)	Graduate Design	Joy
Chen, Jacques, & Sobhanigavgani (2019)	Electrical & Computer Engineering	Clearly problematic matters
Coulson & Harvey, 2013	SoTL	"Challenges to beliefs, values, and assumptions as well as cultural and other conventions" (p. 408); during reflection-in-action, "processing issues, incidents, and emotions; making sense and developing meaning from experience; applying theory to practice" (p. 409)
Cosgrove, Ryan, & Slattery (2014)	Civil Engineering	Triggering event, puzzlement, recognition
Cosgrove & O'Reilly (2020)	Civil Engineering	An awareness exists that causes a shift from knowing to a holistic review and/or reshaping of processes
Davies (2006)	Economics Education	A recognition that two contexts are identified with a "common foundation" (p. 81) which leads to integration and synthesis
Douglas et al. (2018)	Engineering & Design Teaching and Learning, K-12	A need exists for change; a need exists for monitoring change in thinking, processes, or products
Dym et al. (2005)	Engineering	Ambiguity
Ge & Leifer (2020)	Engineering Education	"four-stage psychological process: schema incongruence (surprise), cognitive dissonance (confusion), pattern recognition (curiosity) and schema resolution (relief)" (p. 661).
Gibson, Kitto, & Bruza (2016)	Education & Analytics	Need exists to connect to a wider world; a need exists for correcting a distortion of view
Hong & Choi (2019)	Instructional Design Learning, Design, and Biotechnology	Surprising, unexpected event; a commitment to reflecting on the event
Householder & Haley (2012)	Engineering and STEM (K-12)	Awareness for connections and future applications
Hutchinson & Tracey (2015)	Design Thinking & Higher Education	Questions about identity
Irvine (2020)	Rhetoric and Writing	A fluctuation between what is real and what is ideal for the solution (p. 23)
Jobst, Thoring, & Badke-Schaub (2020)		"Only in the moment when a cue indicates newness, surprise, or danger, the activity of reflection can be initiated" (p. 2)
Kember et al. (2008)	Teaching and Learning	"a change in perspective over a fundamental belief" (p. 379)

Research	**Field**	**Themes**
Kim et al. (2019)	Engineering	“joyful discovery in ‘aha moments’ as well as ‘valuable insights from others’” (p. 11)
Kim, Suh, and Song (2015)	Design Based Learning	Joy, excitement
Kholidi et al. (2020)	Mathematics Education	“A question that can cause a problem solver’s perplexity” (p. 20)
Land, Rattray, and Vivian (2014)	Digital Learning	A “dark tunnel of liminality” (p. 209)
Mina, Cowan, & Haywood (2015)	Engineering Education	Doubt, hesitation, perplexity, or mental difficulty
Melzer & Hacker (2015)	Design Thinking, Engineering, & Psychology	Need for improvement of solution/procedures
Meyer & Land (2006)	SoTL Digital Learning	Troublesome knowledge, disruption, a sense of loss
Micheli et al. (2019)	Product Innovation and Business Management	“Wicked problem solving, constraints as inspiration” (Table 3., p. 132)
Middendorf & Pace (2004)	Interdisciplinary Education	Setbacks, bottlenecks
Moon (2004)	Reflection and Experiential Learning in Education	“[R]elatively ill-structured, complex, or unpredictable” (p. 102) situation where learner intends to cope and to make meaning; new material challenges internal experience or intent of the learner; difficulties in representing new material exist; secondary material results from a challenge, and it presents new challenges
Nachowitz (2018).	Mathematics Education	Prompt for test corrections and error analysis: “What went wrong?” (p. 9).
Patel & Dasgupta	Engineering Design	Triggers causing reflection: elements of the design problem, testing, information related to context, resources provided, externally prompted questions (p. 288).
Perkins (2006)	Teaching and Learing	Conflicts with foreign, alien, or difficult knowledge; challenges with threshold concepts and “underlying epistemes” (p. 45); “particularly tough conceptual nuts”
Reidsema & Mort (2009)	Engineering Education	Joy, shock, happiness
Schön (1983, 1987, 1995)	Teaching and Learning	Situational talk back
Sen & Ford (2009)	Library Information Services	A “sea-change” (p. 181); a triggering event, influence from someone, or action; a catalyst clearly defined and understood; a need to analyze multiple perspectives for a future action
Tracey & Hutchinson (2016, 218))	Design Thinking & Higher Education	Conflict, uncertainty, aversion, belief change, emotional reaction, questions of identity, awareness of multiple perspectives, values, assumptions, recognition for consequences
Wald et al. (2012)	Medical Education	Conflict, disorienting dilemma, complexity, & moral challenges
Walther et al. (2007, 2009, 2011) in Epstein & Zastavkar (2017)		Emotional triggers

Figure 1

T/E DBL and Related Cognition



Exigences

Scaffolding reflection and CRWTL requires an awareness of exigences for emotional reactions in T/E DBL because exigence impacts learners' impetus to solve design problems and pursue threshold concepts in the design space. Themes for exigence in the literature reviewed variously intersect with the affective, cognitive, social, and psychomotor domains of DT, as framed for engineering instructional design constructed by Vanasupa, Stolk, and Herter (2009). For example, the research highlights emotional reactions, while other research emphasizes reactions to interpersonal demands and activities. Regardless, without dedication, learners will not thoroughly address major changes in their schema necessary for enhancing their willingness to learn about their own design thinking.

Table 2

Synthesis of Topics for Bounding Critically Reflective Exigence in T/E DBL Domains (Vanasupa, Stolk, and Herter, 2009)

Affective Domain	**Cognitive Domain**	**Social Domain**	**Psychomotor Domain for Understanding Form and Function (deVries, 2008)**
Reflection for Action	Reflection in Action	Reflection on Action	Reflection on Future Worlds
Intrapersonal Point of View	Interpersonal Point of View	Sociotechnical Point of View	Material Point of View
Artefact and Interpersonal Schema	Artefact and STEM-Integrative Knowledge	Artefact and Communication	Artefact and Situational Constraints
Phases for DT Impacting Analogy	Phases for DT Impacting Conceptual Understanding	Phases for DT Impacting Collaboration and Other Social Necessities	Phases for DT Impacting Material Handling and Activities
Low Reflection	**Understanding**	**Reflection**	**Critical Reflection**
Describe, Narrative, Report, React, Summarize Genres for WID Idea Fixation Habitual Actions Tacit Knowledge and Practices	Analyze, Compare, Attribute Cause, Relate Part to Whole, Relate Whole to Part Genres for WID	Draw Analogies to Interpersonal Knowledge & Practice Recognize Connections Bridge Past and Present Knowledge, Practices, Activites Genres for Reflective WTL Interpersonal Knowledge	Recognizes need for a change in intrapersonal schema, develops intention, recognizes changes to enact and enacts these changes, invests in seeing changes through, endures alterations, develops meta-awareness for impacts of decisions in holistic sytems, considers unforeseen circumstances related to domains, reshapes ethical frameworks, reflects on an ecology of interactions and intrapersonal identities in extra-personal systems, enacts changes and invests in seeing the changes through, develops awareness for interactive/hermeneutical aspects of the artefact and what it realizes in complex social systems, bridges past to present to future, Genres for CRWTL employed, increased professional identity, increased self-efficacy
Memorizes and Enacts Algorithmic Operations and Activities, Entrenched Knowledge and Actions	Explores New STEM Connections	Relates STEM Knowledge to Artefact/Activities for Design	Reshapes habituated STEM Knowledge for Design, iterates and decides with meta-awareness for sitution
Induction **Divergence** **Convergence**	**Deduction** **Divergence** **Convergence**	**Abduction** **Divergence** **Convergence**	**Metacognition**
Define Need and Situational Constraints	**Relate, Research, Ideate**	**Ideate, Design, Test, Redesign**	**Finalize Artefact**
Invention	**Arrangement**	**Style**	**Inscribe/Remember/Deliver**
Kairos/exigence	**Appeals**	**Thesis/Antithesis**	**Synthesis**

Conclusion

The current paper is a snippet of dissertation research that intends to study CRWTL in the demanding, iterative phases of T/E DBL for iterative prototyping. The first step has been to explore how to bound the intervention and write the prompt. Understanding intrapersonal exigences significant for critical reflection has been informed by the literature review, and these indicate that the prompt needs to address myriad ways people react to hands on T/E DBL. Before integrating the CRWTL prompt, instructors need to scaffold designers' awareness of possible exigences for their critical reflection and help them recognize the affective and other dimensions of these exigences, so they can write about these. This research contributes to T/E because it has begun to manifest ways educators can develop more sensitivity to the ways students could be responding to threshold challenges in DT throughout DB, so they can scaffold for CRWTL accordingly.

Keywords and Definitions

Acronyms

CT: Composition Theory
DBL: Design-Based Learning sometimes called Designing to Learn or Engineering by Design)
DT: Design Thinking (the individual's embodied and holistic acts that happen during design)
FYE: First Year Engineering
LTW: Learning to Write
PBL: Problem/Project-based Learning (sometimes used interchangeably)
SoTL: The Scholarship of Teaching and Learning
T/E: Technology and Engineering Teaching and Learning
T/E DBL: Technology and Engineering Design-based Learning
WAC: Writing across Curricula and Contexts (implies interdisciplinary writing strategies exist)
WAW: Writing about Writing and/or Reflection on Writing (reinforces strategic writing)
WID: Writing in the Disciplines (writing that is significant for intradisciplinary practice)
WFT: Writing for Transfer (writing used to transfer targeted domain knowledge and practice)
WTL: Writing to Learn (transdisciplinary writing practices used in liminal places for formative learning)

Definitions

Critical reflection.

Unlike non-reflection and reflection, critical reflection bridges intrapersonal schema for past, present, and future, and it happens when an experience that is threshold for the individual causes an emotional effect which alters that individual's intrapersonal schema so much that the person thinks or acts differently, and there has been a recognition and repositioning of that person's intrapersonal schema. It is agreed that scaffolding for critical reflection seems necessary for advancing metacognition in less-expert learners. Stakeholder perspectives for what is threshold in a discipline or practice has not always correlated with what learners recognize is threshold for them, so while assessing for benchmarks is important, it is also important for educators to recognize exigences and impacts for students' intrapersonal critical reflective performances in the classroom.

Critical Reflective Writing to Learn.

CRWTL is a term created for this dissertation research. CRWTL is a way to intentionally scaffold low-stakes writing to heighten learners' awareness for critical incidents they are personally experiencing in their learning. Various genres could be leveraged for CRWTL in T/E

DBL during its iterative phases, such as the design journal, online E-portfolios, or designers' memos to self. However, CRWTL requires scaffolding. Learners are not naturally aware of the importance for writing and recording their critical reflections, yet doing so supports long term metacognitive critical thinking.

Writing.

Writing is a "technological device," a "unique language process," and a "mode of learning" (Emig, 1977) graphically produced and delivered according to the constraints of a particular rhetorical situation. Because recorded writing transects situation, time, and space (Baron, 1999), reaching imagined or unanticipated audiences. Writing results from "the writer's goal-directed monitoring and control" (Hacker, Keener, & Kircher in Hacker, Dunlosky, & Graesser, 2009, p. 170), so writing is "applied metacognition," (p. 170) that "reflects the unique phenomenology of an individual" (p. 156) during the individual's processes and productions. Writing is a graphic, alphanumerical "sign-using activity" (Vygotsky, 1978), and it is an unnatural language function (Vygotsky, 1978; 1934/2012) learned from others (Emig, 1977; Vygotsky, 1978; 1934/2012).

Because writing is unnatural and must be learned from others, it requires "scaffolding" (Wood, Bruner, & Ross, 1976) that promotes interactions between less-expert writers and more-expert writers that advance language and rhetorical awareness (McCarthy, 1930/1946; Wood, Bruner, & Ross, 1976; Vygotsky, 1934/2012; 1978). Within social constructivism, writing, in contrast to speaking, is a slower way for individuals to learn, because it integrates intrapersonal and interpersonal realms where the writer is "shuttling among past, present, and future" (Emig, 1977, p. 13) knowledge and awareness.

Writing exists on a spectrum from inner- to outer-directed (Bizzell, 1982), so writing is a reflective and integrative act that demonstrates varying degrees of reflection and reflexivity, and these depend on the writer's goals in a particular situation (Hacker, Keener, and Kircher, 2009). Since writing slows thinking and action (Emig, 1977), it can be a tool for reflection, communication, and feedback in complex "discourse communities" (Swales, 1988, 2014, 2020) that have generic activity systems (Russell, 1997) involved with its invention, performance, and production.

Writing is contingent on and shaped by these complex rhetorical situations and their constituents (Downs, 2020; Grant-Davie, 1997). As an authentic, embodied and "emplaced physical activity" (Rule, 2019, p. 8), writing is not just a disambiguated cognitive process or rhetorical abstraction. Rather, it is an "integrative" (Huber & Hutchings, 2004; Huber and Hutchings, 2005; Huber, Hutchings, and Ciccone, 2011) agent for hands on problem solving.

Meaning making through writing causes interactions between the real world and the writer. Writing can a hermeneutical medium available for invention and prototyping, since it supports "a way of engineering materials in order to accomplish an end" (Baron in Wardle and Downs, 1999/2017, p. 634, inset), and it can describe active hands on DT. Finally, writing exists as concrete evidence used for describing experiential learning (Moon, 2004).

Critical reflection.

Unlike non-reflection and reflection, critical reflection bridges intrapersonal schema for past, present, and future, and it happens when an experience that is threshold for the individual causes an emotional effect which alters that individual's intrapersonal schema so much that the person thinks or acts differently, and there has been a recognition and repositioning of that person's intrapersonal schema. It is understood that scaffolding critical reflection is necessary for advancing metacognition in less-expert learners. Stakeholder perspectives for what is threshold in a discipline or practice has not always correlated with what learners recognize is threshold for them, so while assessing for benchmarks is important, it is also important for educators to recognize the exigences and impacts for students' intrapersonal critical reflective performances in the classroom.

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