TEACHING DESIGN: FROM DUELING TO ‘DUALING’ THRESHOLD CONCEPTS

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ABSTRACT

Engineering students encounter many threshold concepts as they learn the design process. These troublesome yet transformative concepts can hinder learners as they transition from novice to informed designers. A parallel and dueling effect can occur as engineering design educators learn to surmount their own threshold concepts in their journey toward proficient and expert teaching. Until educators develop Design Pedagogical Content Knowledge (D-PCK), their students may continue to struggle as they work to overcome the troublesome elements of design. This paper proposes a framework to support the professional learning of engineering educators as they develop D-PCK. Acquiring this competency helps facilitate a shift from dueling to ’dualing’ threshold concepts where educators who make the effort to overcome their own teaching-related threshold concepts become better equipped to support learners as they become better informed designers.

KEYWORDS

Engineering education, threshold concepts, design education, educational development, evidence-informed teaching, Standards: 10

INTRODUCTION

Although engineering design is an integral and requisite part of undergraduate engineering programs, it is inherently difficult for students to learn and educators to teach. Students struggle with seemingly ambiguous processes required to solve open-ended and complex problems in an educational system where they’ve been taught to analyze and seek out the one ‘correct’ solution. Similarly, engineering educators are encouraged to break away from the lecture-based instructional approaches ingrained in higher education and move toward more student-centered approaches. These coinciding challenges set up an environment where both students and educators are simultaneously expected to radically transform their ways of thinking and doing. This is not an easy undertaking since reluctance (or resistance) on either or both parts can set up conflicting interests, a duel of sorts.

Systematically designing solutions to complex, open-ended engineering problems is an holistic process that requires students to demonstrate competence in specific design strategies, many of which are difficult and troublesome. Educators must bring their own professional design experience to the process, along with a reflective understanding of how they themselves learned to think through, and talk about, design problems. With appropriate guidance, both students and educators can thrive during these transformative experiences. Students need an effective learning environment for design, and educators need discipline-specific educational development to teach design effectively. This paper presents a framework that ‘duals’ the support required by both to provide a rich and rewarding design experience.

SCHOLARSHIP OF INTEGRATION

Frayling suggests there are three types of design research: (1) research *for* design where design is the purpose and the focus is on a product, (2) research *into* design where design is the subject and the focus is on design itself, and (3) research *through* design where design is a method and the focus is on learning about what you design (Frayling, 1994). As engineers we typically do research *for* design using that research to prepare for and inform our solution. As engineering educators we need to broaden this thinking to include research *into* design so we are cognizant of the practices, methods and tools that support students as they learn to become designers. We must also tap into the work of those doing research *through* design that informs how design can be taught.

Teaching engineering design requires the integration of findings from each type of design research. Those findings come not only from our own disciplines, but also from cross-disciplinary areas such as design, and education. For this reason, scholarship of integration is used as the foundation of this work. Its purpose is to interpret and integrate the research findings from other disciplines to create and share interdisciplinary solutions to existing problems (Ream, Braxton, Boyer, & Moser, 2016). This study integrates the findings of research in: (1) design, (2) threshold concepts, (3) engineering design education, (4) pedagogical content knowledge, and (5) faculty development.

DESIGN EDUCATION

Schon, in his design-constructivism model for higher education, suggests that design is “learnable but not didactically or discursively teachable” (in Waks, 2001). He proposes that design is best learned through practice, where students acquire and apply tacit knowledge and discipline-specific language in a setting that emulates the work place. This process requires experienced practitioners to supervise and coach students through graduated, level-appropriate, authentic problems as they experiment, assess, think, and discuss.

Over the past three decades design thinking has emerged as a way to question current states, conceive what does not exist and to help address “wicked” problems (Buchanan, 1992). When faced with these vague, ill-formulated problems with no definitive conditions or limits, designers must draw upon key attributes such as creativity and innovation, user-centeredness and involvement, iteration and experimentation, and tolerance for ambiguity and failure (Micheli, Wilner, Bhatti, Mura, & Beverland, 2019).

Engineering design students face additional discipline-specific challenges when faced with wicked problems (Lönngren, 2017). The highly-paradigmatic nature of engineering limits their ability to see multiple viewpoints and perspectives, which is necessary for problem formulation, solution approaches and solution evaluation. Students also consider knowledge as ‘certain’ or factual and, as a result, expect unambiguous problem descriptions that should have “correct” solutions. This can create a reluctance to act when faced with uncertainty, ambiguity, and expectations beyond the discipline. It is only when students cross this threshold and can tolerate being in this state of uncertainty that they become confident to challenge wicked problems (Osmond & Turner, 2010).

Many of the challenges associated with wicked problems are considered threshold concepts. These discipline-specific concepts or skills must be mastered, but because of their nature, present unique learning challenges for students (Meyer & Land, 2003). A threshold concept has five characteristics that distinguish it from a core concept: (1) it is uniquely troublesome, challenging the way learners think, often making the concept intellectually and emotionally uncomfortable to master, (2) it is integrative, pulling discrete concepts and ideas together into new ways of thinking or understanding, (3) it transforms the way learners think about their discipline, (4) it is considered irreversible, and (5) it is bounded to one's discipline and dependent on context. Mastering a threshold concept is different for each learner. The experience of moving from not knowing to knowing is called liminality and can be quite disorienting for learners (Meyer & Land, 2003). Crossing these thresholds can make the difference in a student's ability to merely carry out engineering tasks versus thinking and acting as an engineer.

Engineering educators have identified a number of discipline-specific threshold concepts, design being one of them. They are curated in an open-access repository of interdisciplinary threshold concepts (Flanagan, 2020). A multi-year study by an Australian research team created a separate inventory of foundational engineering threshold concepts and capabilities grouped into three main categories: (1) learning to become an engineer, (2) thinking and understanding like an engineer, and (3) shaping the world as an engineer (Male, 2012). The 'shaping the world' category includes threshold concepts associated with design and problem solving. This research team identified troublesome features such as variability in the real world, approaching open-ended problems, justifying answers, and integrating multiple topics and sources of information, all of which are required to address wicked problems.

Many engineering educators do not use the term threshold concept, but recognize them as key concepts and skills that are considerably more difficult to learn and that should be emphasized. Over the years, educators have identified a number of design-related cognitive processes and soft skills that make design difficult to learn. Students must tolerate ambiguity and easily switch between divergent and convergent thinking. They must focus on the big picture and frame problems instead of trying to solve them. Their design process must be managed, iterative and reflective. Students must generate many ideas and balance benefits and tradeoffs to make justifiable decisions. They must also perform diagnostic troubleshooting, and unbiased tests and experiments. They must think and work as part of a team and communicate their ideas and design using different representations and languages such as verbal/textual, graphics, mathematics and numbers (Dym, Agogino, Eris, Frey, & Leifer, 2005) (Crismond & Adams, 2012). Engineering design educators must be aware of and modify their teaching practices to support students as they encounter these troublesome elements of design.

TEACHING DESIGN

Engineering education research also suggests that teaching design requires a paradigm shift for educators (Heywood, 2005) (Woods, 1996). It requires changes in the way content is delivered and learning is assessed, and shifts the focus from product-driven "right answers" to process-driven optimal solutions. As a result, educators need to hone facilitation and coaching skills as part of their teaching practice.

Connecting research on how to design with research on how to teach identified nine design strategies, contrasting patterns of novice and informed designers, relevant learning goals, and instructional approaches that support student learning. Each design strategy corresponds to an aspect of the design process such as understanding the challenge, representing ideas, and troubleshooting (Crismond & Adams, 2012). Their Informed Design Teaching and Learning Matrix suggests that design educators must develop their own pedagogically-sound way of teaching design so that learners can overcome these difficult and troublesome elements.

The concept of Pedagogical Content Knowledge (PCK) has evolved since it was introduced by Shulman in 1986. Initially described as the integration of content knowledge and pedagogical knowledge, it helps educators recognize what makes concepts easy or difficult to learn, package content for optimal learning, and help students organize their learning (Shulman, 1986). A recent literature review of PCK in science suggests that the development of PCK is actually more complex than first thought (Azam, 2019). It proposes a conceptual framework where PCK is an amalgamation of topic-specific PCK formed through experience and reflection when teaching-related knowledge integrates with conceptual knowledge. The nine dimensions of pedagogical knowledge (student learning, assessment, curriculum, goals, instructional strategies, resources, technology, student diversity, and contexts) are closely related to teacher-related threshold concepts.

Many engineering educators don't recognize that they too encounter threshold concepts that can hinder their individual journeys to becoming effective educators. These can be clustered into four actionable areas in which educators can grow: (1) pedagogy, (2) learning, (3) assessment, and (4) educational technology (Nelson & Brennan, 2021c).

Crossing pedagogy-related thresholds requires educators to develop Pedagogical Content Knowledge (PCK), the ability to teach one’s subject effectively (Shulman, 1986). This means identifying the "ways of representing and formulating the subject to make it comprehensible to others" (p. 9). One such threshold concept is simply acknowledging the existence of threshold concepts. Educators who cross this threshold recognize that there are specific concepts that are essential to thinking and practicing within their discipline (Adler-Kassner & Wardle, 2015). With this comes the need to adapt teaching practices to support students as they shift from doing discipline-specific things to becoming practitioners (O’Brien, 2013).

To cross learning-related thresholds, educators must learn more about how students learn, find ways to better engage and motivate them, and explore ways to provide choice in how learning is demonstrated. Crossing the assessment-related thresholds requires moving from norm-referenced to criterion-referenced evaluations. This depends on the successful alignment of assessments, clearly enunciated learning outcomes, and meaningful learning opportunities that provide supportive and informative feedback to students. To cross the teaching with technology thresholds educators must acquire Technological Pedagogical Content Knowledge (TPACK) to stretch their current teaching practices to include appropriate educational technology (Koehler & Mishra, 2013).

The LENS (Learning Environments Nurture Support) model for engineering faculty development emerged from the integration of transdisciplinary research (Nelson & Brennan, 2021b). The model, shown in Figure 1, uses a systems approach (Henkin, 2007) to shift the focus of educational development from teaching to that which best supports learning. Its six ‘lenses’ correspond to the elements of an effective learning environment (Nelson & Brennan, 2019), each featuring the dimensions of pedagogical knowledge required to master teaching-related threshold concepts.

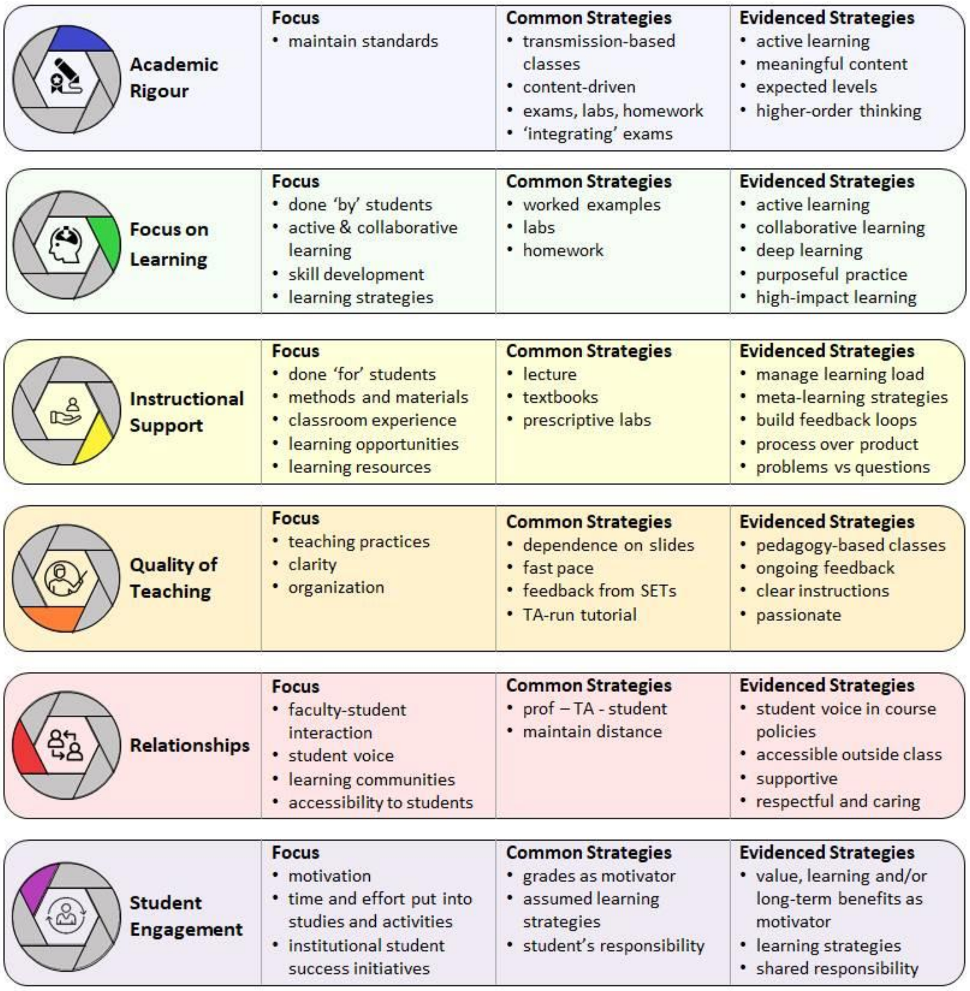

Figure 1: LENS framework for engineering faculty development

DUAL FRAMEWORK FOR DEVELOPING DESIGN PEDAGOGICAL KNOWLEDGE

Crismond and Adams identify Design Pedagogical Content Knowledge (D-PCK) as a design specific form of PCK that characterizes the way teachers use teaching techniques to convey design thinking knowledge and help students develop as design thinkers (Crismond & Adams, 2012). Their general suggestions for developing D-PCK include clearly articulating and scaffolding learning, finding meaning and providing guidance in the way one teaches, breaking the fourth wall to create a teaching moment when appropriate, and allowing students to figure things out on their own. While they suggest specific teaching strategies for each of the nine design patterns, their model does not consider the 'duel' between educators challenged to master teaching-related threshold concepts, and learners encountering the troublesome aspects of design.

The DUAL (Design Unleashed through Adept Leadership) framework addresses these dueling threshold concepts (see Figure 2) by examining four distinct, yet related, elements of engineering education: (1) the learning space, (2) the students, (3) the engineering design educator, and (4) the faculty development for those educators. Prior to exploring each level, it is important to recognize that engineering students are typically conditioned to learn in their engineering science courses, the majority of which are teacher-directed and lecture-based (Nelson & Brennan, 2018).

The left side of the DUAL framework shows the teaching and learning elements of a conventional engineering science course. The learning space is a classroom or lecture hall in which students listen to lectures. Assessments are traditional (exams, tests, assignments and labs) where problems have one “correct” answer. Students must demonstrate the knowledge (K) and skills (S) needed to pass the course, and acquire the attitudes (A) required to be a successful engineering student. Most of these engineering science courses involve at least one discipline-specific threshold concept that students are expected to grasp and integrate into their conceptual knowledge base. The educator, depending on their experience and commitment to teaching, brings PCK to the learning space. The quality of that PCK depends on how many of the teaching-related threshold concepts have been mastered. Research shows, however, that many engineering faculty choose not to develop their teaching skills, even though institution-wide and/or school-specific faculty development units offer myriad opportunities to do so (Felder, Brent, & Prince, 2011). This may explain why national student engagement surveys rank the effectiveness of the undergraduate engineering experience lowest among the disciplines (Nelson & Brennan, 2021a).

The right side of the DUAL framework shows the elements of an effective engineering design experience, each of which is encompassed by an aspect of professional practice. Here the learning space is design-focused with students learning the performance dimensions related to informed design, and educators modeling discipline-specific language and practices. There are concepts to be taught and modeled, and skills and processes to be learned. Assessments stretch beyond the traditional to include regular, formative feedback on design-related tasks. The design space emulates an engineering workplace where the educator takes on a technical leadership role, mentoring and coaching students as they work to become informed engineering designers.

Students are asked to design solutions for authentic, level-appropriate engineering problems in this design space. They must show that they can apply the knowledge and skills they’ve learned in their engineering science courses, including the discipline-specific threshold concepts they may or may not have yet mastered. They are expected to demonstrate knowledge and skills beyond the technical body of knowledge, recognizing that employability-related and professional skills are instrumental for effective engineering design. These aspects of professional practice include, but are not limited to, communicating and defending engineering decisions, team work, and project management. Students also encounter new design-specific threshold concepts as they take their design skills from beginner to informed designer.

To support design learning, educators must specialize their PCK to include D-PCK. This requires ongoing development within each of the nine pedagogical knowledge dimensions, and efforts to cross the pedagogical, assessment, learning, and technology-related teaching threshold concepts. It also requires development of solid facilitation skills, a key requirement in effective technical leadership. This includes asking leading and open-ended questions, helping students reflect on their design experiences, monitoring student progress, challenging student thinking, raising issues that need to be considered, and establishing a environment where students feel safe to ask questions and make mistakes (Woods, 1996). To this point, facilitation has not been identified as a specific teaching-related threshold skill although myriad researchers identify it as required to support students as they encounter threshold concepts in their disciplines (Flanagan, 2020).

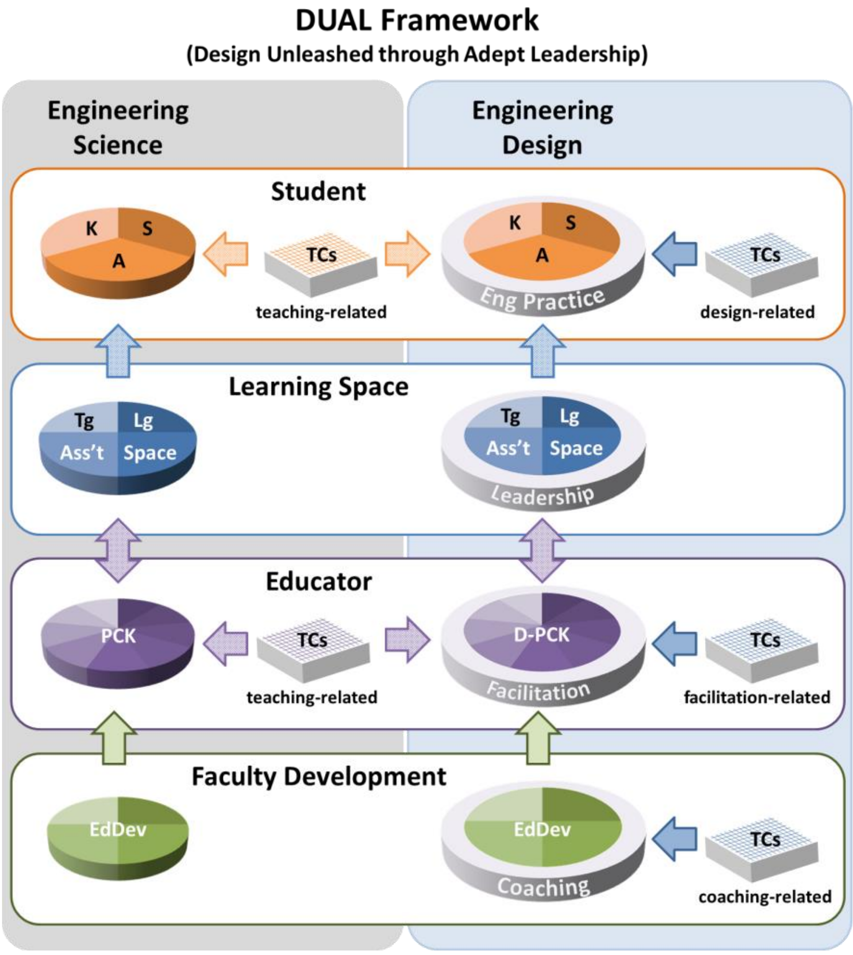

Figure 2: DUAL Framework

Most educational development units focus on five key areas: (1) teaching and supporting learning, (2) professional learning and development, (3) mentorship, (4) research, scholarship, and inquiry, and (5) educational leadership. The professional learning and development area supports the growth of educators' PCK, but rarely includes learning opportunities to develop the facilitation or coaching skills required for design education. Mentoring from industry advisors, sponsors or engineers-in-residence would be the optimal way to acquire and practice these facilitation skills. Workshops could provide similar benefits for engineering design educators, should mentoring not be feasible.

The DUAL framework examines the teaching and learning challenges associated with engineering design education. Initially assumed to be a 'dueling' of teacher- and design-related threshold concepts, the contrasting of four aspects of engineering science and engineering design classrooms brings to light other significant and challenging facets that must be acknowledged. First, the learning space must be a safe and supportive environment facilitated by educators who are well-practiced in engineering design. These educators must develop and use adept technical leadership skills to support students as they attempt to master design-related threshold concepts. Next, engineering design courses cannot assume students are equipped and able to apply and integrate discipline-specific threshold concepts and/or skills associated with professional practice. Learning opportunities and resources should be prepared and in place should students need additional support. Finally, educators must continually develop their PCK and D-PCK through focused and supportive faculty development. These learning opportunities should be tailored for engineering educators and extended to provide evidence-informed graduated support related to teaching, discipline and design-related threshold concepts, leadership, and facilitation.

FUTURE WORK

Each aspect of the DUAL framework provides avenues for further study. At the student level, work can be done to explore the dueling of discipline- and design-specific threshold concepts. This could determine whether the choice of design problems that assumes mastery of discipline-specific threshold concepts affects students' abilities to master design-related threshold concepts. At the learning space level, further work could measure the type and adeptness of technical leadership supporting student learning. This would refine the definition of D-PCK and help shape the development of technical leadership in engineering education. Further work can also be done to examine the impact differing facilitation skills have on the students' design skill development.

The DUAL framework also suggests facilitation skills, and the educational development of these skills, may be threshold concepts. Further work could determine if either or both meet the five associated criteria.

Finally, the LENS model for engineering faculty development will be enhanced to include a focus on recognizing design-related threshold concepts, developing D-PCK through facilitation and technical leadership, and recognizing the effect dueling threshold concepts have on student learning. Use of this engineering design-specific model, LENS-ED, could be monitored to determine its impact on the continued pedagogical growth of engineering educators involved in transforming students from novice to informed designers.

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