How are Threshold Concepts Applied? A Review of the Literature

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How are Threshold Concepts Applied? A Review of the Literature

Abstract

Funded by a recently awarded NSF RED grant, we aim to transform the curriculum and culture of a large electrical and computer engineering department with a model that foregrounds design and innovation to offer students a variety of pathways to a degree. We are developing a combination of approaches to create a program with disciplinary depth and a range of learning experiences, including a participatory design approach that involves not only curriculum redesign, but also engagement of faculty and students in industry and K-12 outreach. Through these combined approaches, we hope to increase the diversity of students entering the program, the variety of pathways through the program, and the kinds of careers graduates pursue.

We begin with the goal of effectively employing the Threshold Concepts Framework to identify transformative targets for curricular revisions. Our first step in approaching the RED grant from the perspective of curriculum develop includes a literature review that both systematically canvases existing resources and summarizes and synthesizes themes that enable us to answer the following questions:

1. What research findings have been reported about threshold concepts across disciplines, in the field of engineering, and in electrical engineering, computer engineering, and computer science?
2. What are the perceived strengths and weaknesses of the threshold concepts framework, both in theory and practice?
3. Which methods are most effective for identifying threshold concepts?
4. How have threshold concepts been used to enact change?

In exploring these questions, we investigate the history and evolution of the threshold concepts framework with attention to sociotechnical patterns such as whether and how “professional” and “technical” concepts are delineated. In terms of methodology, we consider whether data collection prompts guide people away from the center of their discipline, and whether there is less of a dichotomy between social and technical than often portrayed in engineering education narratives.

Finally, we are employing a participatory design process in which we are not only asking department stakeholders to identify sites of threshold concepts, but also to enroll them in a grass-roots, transformative effort. To that end, we explore ways that the process of understanding threshold concepts serves as an opportunity for dialog that can kick-start the culture shift of the department.

This paper will be framed as a literature review beginning with the seminal three volume collection on threshold concepts (edited by subsets of the team Ray Land, Jan Meyer, Jan Smith, Caroline Baillie, and Michael Flanagan), a search of ASEE and Frontiers in Education proceedings, then concluding with the Education Research Complete database for other relevant articles between 2003 and 2016. In this review, we will (1) summarize the theory of threshold

concepts, (2) identify what threshold concepts have been proposed in both Electrical and Computer Engineering, (3) explain how the concepts have been used in curriculum development to enact change, and (4) discuss how the existing literature will inform our participatory design process in revolutionizing the ECE department.

Introduction

Faced with critical feedback from industry on the lack of opportunities for students to gain professional skills and a persistent challenge of increasing diversity in the undergraduate population, the ECE department at Virginia Tech is poised for substantial change. Engineering education can be thought of as a process of holistic formation in which aspiring professionals develop scientific understanding but also define and solve real-world problems, collaborate in teams, and critically explore the ethics and values of their work; yet, the current curriculum is populated by traditional engineering courses that follow the typical formula of lectures, close-end homework problems, and exams. Pathways in and out of the program are also scarce, influenced primarily by an assortment of required courses that fill much of student check sheets. In our plan to enact change to diversify the ECE department in terms of student make-up and concentrations to choose from, identifying critical points in the student's trajectory toward degree completion was made the first course of action.

To adopt a frame through which we can examine the curriculum, the idea of *threshold concepts* proved to be an attractive foundation for the department's reinvigoration. When facing issues early in their studies, students may think to themselves: "How can I be an electrical engineer if I don't understand the difference between current and voltage?" Within the engineering curriculum, certain concepts exist that not only can leave students scratching their heads, but also feeling like less of an engineer if the idea doesn't stick - most likely in a less explicit manner than the initial quote. Such is the nature of *threshold concepts*[1], which emerged from the field of Economics[2] and have been applied across the disciplines. Threshold concepts have implications in electrical and computer engineering to not only identify critical roadblocks in students' understanding, but inform pedagogical practices as well.

To ground threshold concepts in terms of instruction and how we assess student understanding, we can retrace our steps and ask the philosophical question, "what is the nature of knowledge and what can be known?" The little school house on the prairie and the modern day elementary school classroom, whether it is practicing language or multiplication tables, typically invoke a behaviorist point of view – stimulus and response. Knowledge is deposited and dispensed upon request; such is the nature of Friere's banking concept of education[3] which abstracts students as vessels to be filled with facts without any conception of meaning. But knowledge that sits dormant within a student's mind is hardly of any use beyond responding to trivia questions or performing simple tasks, which leads to the intention of Horace Mann with his construction of the common school – to instill conceptual understanding beyond *inert knowledge*.[4]

Certainly conceptual understanding is a noble goal in the classroom, but the idea of *transfer* is often hailed as the most significant objective in education.[5] In transfer, the student can take a portion of his or her knowledge and apply it in a different context. Since transfer is notoriously difficult to achieve, threshold concepts can be a useful alternative framework for educators who want to prepare their students for a profession.[6] The framework of threshold concepts distinguishes itself from transfer in the sense that it lays the conceptual pathways to support students applying skills in different contexts, but also functions as an integrative manner of thinking about a domain.[1] Ideas that may have been previously unrelated suddenly become connected; for example, the connection between differential and integral calculus – two completely different theories with a bridge uniting the two. The understanding of threshold concepts in Electrical and Computer Engineering is developing, but researchers can take a note from Computer Science – a field that has both embraced and shunned the theory at various points in its history.

This paper will be framed as a *literature review*. To begin, we will (1) summarize the theory of threshold concepts, (2) identify what threshold concepts have been proposed in both Electrical and Computer Engineering and Computer Science, (3) explain how the concepts have been used in curriculum development to enact change, and (4) how the existing literature will inform our participatory design process in revolutionizing the ECE department.

Approach to Locating Literature

The authors wished to (1) locate existing identified threshold concepts in electrical engineering and computer engineering and (2) document the common methods of identifying the concepts. The literature review began with a search of the three volumes of threshold concept literature published between 2008 and 2016: Threshold Concepts in the Discipline (edited by Ray Land, Jan Meyer, and Jan Smith), Threshold Concepts and Transformational Learning (edited by Jan Meyer, Ray Land, and Caroline Baillie), and Threshold Concepts in Practice (edited by Ray Land, Jan Meyer, and Flanagan). The texts were culled for articles related to electrical engineering, computer engineering, and computer science so long as one or more of the disciplines were mentioned in the body of the article. Due to the tight-knit nature of the community researching the threshold concepts framework, the authors found the choice of volumes to be appropriate.

Moreover, the search departed from the three central volumes and expanded to the databases of two popular engineering education conferences, the ASEE annual conference and the Frontiers in Education conference. Due to the limited literature, no restrictions were placed on the publication year. After exhausting the available literature, the authors utilized Education Research Complete to locate other articles outside of the previous databases by using the desired fields as keywords in addition to the six qualities associated with threshold concepts presented in the prelude, "Threshold Concepts" (Table 1). At this stage, the review is on-going and the paper presents the authors' findings thus far.

The Threshold Concept Framework

Before discussing threshold concepts with respect to Electrical and Computer Engineering, we first must define what qualities a concept should have to earn the qualifier, "threshold."

What are Threshold Concepts?

A threshold concept is *troublesome* as it is not easily conveyed or understood.[2] The trouble can stem from the fact the knowledge is from an unfamiliar perspective (called alien knowledge), not explicitly taught (tacit), learned without a context (inert), applied on blind faith (ritual), and/or is counter-intuitive (conceptual). The troublesome knowledge is often abstracted as the student's passage through the *liminal space* (Figure 1), a space of discomfort and transformation while grasping a concept.

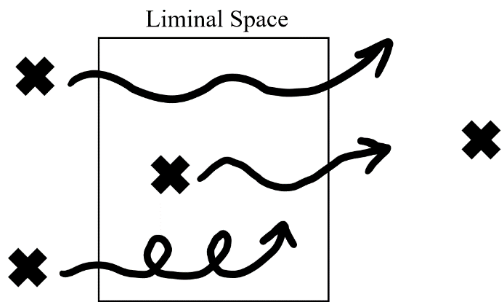

Figure 1: Passage through the liminal space

Students can start on either side of or within the liminal space. Those on the right have either already experienced the transformation or did not find the concept troublesome. The students to the left have yet to experience the transformation and could have different trajectories through the liminal space, as indicated by the lines; in fact, the duration of their stay could be indefinite, and thus cause persistent difficulties for the student. Moreover, a student could feasibly remain in the liminal space, but still manage to "succeed" by memorizing the course material until they are tasked to apply their knowledge to an ill-structured problem – at which point, they become uncomfortable and flounder.

Threshold concepts have primary characteristics/qualities that are necessary to be deemed membership, but other secondary characteristics can be observed.[2] The primary characteristics, *transformative* and *integrative*, and the secondary characteristics, *discursive, bounded, reconstitutive,* and *irreversible* are summarized in Table 1.

Table 1: Summary of Threshold Concepts Qualities

Quality	Description
Primary	
Transformative	**Must** involve a cognitive shift and **potentially** a shift in identity.
Integrative	**Must** "tie" ideas together in students' mental models.
Secondary	
Discursive	**May** enhance the students' ability to communicate precise language.
Bounded	**May** only apply to one discipline.
Reconstitutive	**May** shift connections in the student's mental models.
Irreversible	Highly **unlikely** to be forgotten.

Perhaps the most prominent aspect of threshold concepts is their *transformative* nature.[4] One manner of understanding the *transformative* criterion is to recall a concept that presented an entirely new lens to view the physical (and perhaps nonphysical) world. For example, from electrical engineering, one of the first ideas that may come to mind is the Fourier Transform of a signal *f(t)*,

$$\hat{f}(\xi) = \int_{-\infty}^{\infty} f(t)\, e^{-2\pi\xi jt}\, dt, \qquad \forall\xi \in \mathbb{R} \tag{1}$$

From a purely mathematical point of view, the transform appears to be an integration over the real line which results in a function of a different variable. Within electrical engineering, the integral acts as a vehicle to an entire different domain, the frequency domain – a new way to think about signals.

The idea of a concept being transformative packages the notion of a student experiencing shifts beyond conceptual understanding; that is, the student's identity can be affected as well.[2] The connection to identity requires an additional layer of reasoning, and one potential can be provided by Social Learning Theory[7] and Vygotsky's Sociocultural Theory.[8] Both theories situate cognitive development in social interactions – under the umbrella of culture. Identity is also cultivated in social interactions;[9] more specifically, part of identity is how people see themselves as part of a group. Tonso[10] provides an understanding of engineering identity development in terms of the culture and social interactions in her work on teams in authentic engineering environments. Threshold concepts provide a link, a manner of understanding or knowledge, which connects a concept to one's identity as part of the electrical engineering discipline; for example, knowing how to read the values on a resistor without a multimeter – a unique, but small aspect of working with circuits—is a type of knowledge almost unique to electrical engineers. Yet, the threshold concept literature does little to articulate the ties to identity despite being a unique feature of this dimension.

The next aspect concerns how to fit into a community and affirm a student's identity; to do so, the student must be able to participate in the community. In terms of Gee's[11] concept of identity – informally, being a "certain kind of person" – the community of engineers can be seen as an affinity group, sharing in a common practice. To practice engineering, it is sensible for the student to be able to communicate as an engineer would, thereby leading us to the *discursive* nature of threshold concepts. By experiencing the shift, the student can enhance his/her ability to use language in the context of a disciple.[2,4]

The next criterion to be a threshold concept is its *irreversibility;* in other words, the knowledge is unlikely to be forgotten.[2] For instructors, the irreversibility quality is particularly critical from a pedagogical perspective. Long after the bridge to understanding is crossed years in the past, teachers can find themselves in the so-called "expert blind spot"[5] and have trouble helping novice students cross the bridge as well. Meyer and Land[2] reported similar difficulties experienced by expert practitioners in their initial survey of threshold concepts.

Threshold concepts are also said to be *bounded* in the sense that they *may* only apply to a single discipline.[4] In the case of the Fourier Transform, the criterion is violated since the transform carries significance in multiple fields that use mathematics as an analytical tool. The lens used in electrical engineering is more specialized, which fits the bounded criterion more appropriately. The requirements for the *bounded* criterion can be weakened depending on one's interpretation of discipline.

While the concept could be locked within its home discipline, it must be *integrative*.[2] In this sense, hidden connections can be unearthed through the shift in conceptual understanding and identity. Note that the connections do not necessarily need to be a form of unification like the Fundamental Theorem of Calculus, which links two completely different areas of study – differential calculus and integral calculus. Rather, from a cognitivist perspective, the shift can simply be a few connections in the students' mental models between a set of topics that were previously unrelated in their minds.[12] These shifts are a rearranging or restructuring of a student's understanding, displaying the *reconstitutive* aspect of threshold concepts.

Unsurprisingly, threshold concepts may be core concepts in a course; however, a core concept cannot automatically be deemed a threshold concept. While the qualities we discussed may lead one to believe the central concepts in his or her course must be threshold concepts, the implication does not necessarily work in both directions, and the same is true for misconceptions. For instance, concept inventories[13] provide insight into items in the curriculum that are potential misconceptions (e.g., Rahman & Ogunfunmi[14]), but such concepts do not always meet the characteristics of being a threshold concept.[4]

Detractors and difficulties with Threshold Concepts

Due to the emergent nature of threshold concepts, few authors have provided critical analyses of the framework. As apparent in the survey of the literature, there are a few issues in practice resulting from the following points made by a small group of researchers.

Rowbottom[15] offers a philosophical examination of threshold concepts and critiques their inherent vagueness and lack of methods to empirically validate their status among other concepts that do not meet Meyer and Land's characteristics. The level of abstraction is a problematic aspect of the threshold concept framework; while one hedges to avoid being too bold with his/her claims, Meyer and Land[2] leave too much to interpretation in the most inconvenient place – the qualities. Barradell[16] contends that the variability contributes to the difficulty in reaching consensus when identifying potential threshold concepts. Rowbottom[15] also takes issue with the focus on the concepts themselves in the sense that knowing the concepts does not necessarily imply any ability. Thus, reframing a curriculum around threshold concepts would implicitly cause assessment of proficiency to change as well.

O' Donnell[17] critiques the hypothesis that the disciplines boil down to a finite set of beliefs that do not change. Boxing students into thinking exclusively like engineers inadvertently bars them from an aspect of interdisciplinarity – the interdisciplinarity of critical thought. The *bounded* nature of the disciplines also separates the disciplines into distinct boxes who each have their own threshold concepts. Despite the difficulties, even the critics of the framework contend the threshold concepts still can be applied constructively – especially in sparking conversations to reframe curricula.

Methods of Identifying Threshold Concepts

A natural next step is to discuss how threshold concepts have been identified in the electrical engineering curriculum. While there is no apparent consensus on the "best" method of eliciting the set of concepts, a combination of the following methods is likely ideal. For example, Kiley[18] used interviews and surveys (content analysis) to triangulate the results of the investigation. As it is difficult to quantify the identification process, the approaches in the literature have been predominately qualitative.[4,19]

Content Analysis

The overarching technique of content analysis involves interpreting and coding written material. One could conduct an analysis of the various assessments used in the course, the overall textbook, or open-ended responses to student or faculty surveys. As an example of faculty surveys, Kiley[18] surveyed twenty-six doctoral supervisors across eleven universities to identify threshold concepts. Content analysis, while potentially useful, does not appear to be method that is popular in the literature.

Interviews / Focus Groups

Another method would be to simply conduct either structured or semi-structured student and teacher interviews to elicit the common threshold concepts in the curriculum.[4,19] An interview protocol used by Male and Baillie[20] in their process of complete curriculum renewal simply involved having participants read a primer to threshold concepts, an introductory paper (by Cousin[21], then discuss possible threshold concepts in the faculty's courses, provide evidence as to the concepts' transformative nature, and elaborate on strategies they have used to teach the concepts in the past. Male and Baillie[20] also used two focus groups of students (7 and 5) with a faculty facilitator; topics of discussion were similar to those from the interview protocol excluding teacher-centric questions like "how have you taught this concept before." Zander et. al.[22] used the same format for semi-structured interviews with students in Computer Science.

While the interviews and focus groups are valuable, it is wise to take faculty interviews with healthy skepticism, as they are prone to the "expert blind spot"[5] – faculty can conflate key concepts for the course with what is important for practice in the discipline.[23] Students can also be poor sources of information for a different reason, as they often consider concepts "troublesome" if they simply do not understand the idea yet – resulting in many false positives that do not agree with expert opinions.[19] However, collecting data from multiple types of participants, including not only faculty and students, but also alumni, individuals in the workplace, and staff and administrators, can strengthen findings.

Discourse Analysis

Capturing threshold concepts in action during the problem-solving process with the additional context of intrapersonal communication can be achieved using the Think Aloud procedure and Verbal Protocol Analysis.[24,25] In this method, student participants can be presented with an authentic scenario with a proposed threshold concept imbedded in the problem explicitly or implicitly that he or she must solve – the entire process is video and audio recorded. Once the session is complete, all recordings are transcribed and coded with a coding scheme selected by the researcher. The language used by the participant can mapped to the dimensions of the Threshold Concept Inventory, perhaps to corroborate the results of another method. For example, while not necessarily a Think-Aloud, Carstensen and Bernhard[26] video recorded students during lab work and analyzed the tapes with respect to the Theory of Variation,[27] their coding protocol.

Delphi Study

A Delphi study can be used to identify threshold concepts in a curriculum. The closest application in Electrical and Computer Engineering is the development of concept inventories, such as the development of an instrument for Digital Logic.[28] The purpose of a Delphi study is to engage a group of participants, sharing a common interest, in three rounds of questioning and iterative feedback to achieve a goal.[29,30,31,32] An upper bound of thirty-five participants is ideal since Delphi studies have the potential to generate copious amounts of data each round and duplicate information tends to emerge more frequently after the suggested maximum.[29,32] To avoid the potential of groupthink, the Delphi procedure can be administered online.

Content Representation (CoRe)

In their investigation of threshold concepts in Computer Science, Shinners-Kennedy and Fincher[33] noted methodological challenges with conventional techniques due to hindsight bias; that is, virtually all methods ask participants to recall – a notoriously unreliable activity.[34,35,36] To compensate, Shinners-Kennedy and Fincher[33] advocated for *content representations (CoRe)*.[37] CoRe provides an explanatory tool to frame threshold concepts by drawing upon pedagogical content knowledge (PCK), content knowledge that is operationalized in terms of teaching.[38]

The method is implemented in terms of a workshop with teachers as participants where a two dimensional grid is completed collaboratively. Across one axis is a list of "big ideas" in the curriculum and the other axis is a series of questions meant to elicit responses based in PCK; for example, "Why is it important for students to learn <big idea>?"[33] Implemented as a Delphi study, perhaps the CoRe methods has promise as a method of identifying threshold concepts in Electrical and Computer Engineering.

What are the Threshold Concepts in ECE and how are they applied?

To frame the discussion on Electrical and Computer Engineering, the brief history of threshold concept generation in a discipline that often shares the same space as Electrical and Computer Engineering, Computer Science (CS), can serve as a useful introduction. CS is an exemplar of a field that has both adopted, shunned, and re-adopted threshold concepts as a framework.[33,39] As noted with the difficulties of threshold concepts, identification and verification of the concepts have proven to be the limiting factors contributing their varying degrees of acceptance.

Unlike Electrical Engineering, the curriculum for Computer Science benefits from Schwill's[40] proposal to structure the computer science curriculum around a set of ideas that is central to the discipline called the "Fundamental Ideas (FIs)" In fact, the FIs framework meshes with the idea of threshold concepts,[22] but FIs are generally not *transformative*.

Recall the example of the Fourier Transform as a change of lens to examine the world – the change of domains. A similar change of lens occurs in Computer Science: Luker[41] argued that Object Oriented Programming requires a completely different worldview, a new lens. In this sense, grappling with Objective Oriented Programming can constitute a *transformative experience*. Zander et al.'s[22] interview with graduating students provided further evidence of the transformative nature of this concept along with support for the other dimensions of threshold concepts. The same investigation uncovered the concept of memory and pointers as potential threshold concepts as well.

In terms of examining the change in identity, a key feature of threshold concepts, Computer Science has done little to explore the *transformative* aspect. Zander et. al.[42] provides one of the few studies connecting threshold concepts and identity; clearly more work needs to be done in this area.

Threshold Concepts in Electrical Engineering

A review of the literature indicates an emergence in the use of threshold concepts. For the sake of organization, this section will be split by common course topics.

In navigating the literature, an attempt to investigate the history and evolution of the threshold concepts framework with attention to sociotechnical patterns was desirable. The surveyed literature from the ECE domain rarely discussed non-technical skills in the context of threshold concepts. Certainly other authors have examined professional skills such as the challenges and opportunities of working in an interdisciplinary team,[43,44,45] but the focus in ECE was underwhelming. As the goal of the awarded NSF-RED grant proposal highlighted using threshold concepts as a shift in culture rather than a simple shuffling of existing classes. Thus, a valuable opportunity has emerged to examine the non-technical threshold concepts situated in the ECE department. In fact, ECE programs beyond the RED grant could benefit from paying more attention to professional skills as central to their respective fields. Such a shift could contribute to changing cultures/creating welcoming environments that in turn promote recruitment and retention of underrepresented populations.

DC Circuits

Troublesome knowledge manifests itself early in the curriculum as students grapple with the concept of voltage and current, as explored by Carnes and Diefes-Dux.[46] The trouble can be attributed to the interdependence of the concepts. For instance, a fundamental idea in basic circuit analysis is that "no current implies no voltage." Ohm's Law captures the relationship beautifully in the linear model, $V = IR$ for voltage V, current I, and resistance R, so one could simply set $I = 0$ and immediately deduce $V = 0$. The simplistic mathematical approach, while valid, is filtered under ritual knowledge[1] as one can easily write an equation and manipulate variables – trivial algebra. The variables V and I could feasibly represent anything when thinking beyond Ohm's Law; thus, while mathematical operations allow the student to navigate the connections through the comfort of algebra, the underlying rationale of *why* the physical relationship is true may not be immediately obvious.

In analyzing circuits, González Sampayo[47] reported that students often struggle to conceptualize the various components as a system; in fact, two types of thinking can be observed, local reasoning and sequential reasoning.[19] In local reasoning, students focus on a single point in the circuit and deduce changes to the components will only result in regional changes in voltages and currents rather than global shifts. Sequential reasoning is marginally better; students believe any change they make will result in shifts after the alteration in a sort of domino effect, but the students neglect the opposite direction – before the change.

Electronics

A staple of the electrical engineering curriculum, electronics, serves as the anecdotal "hard" class that drives fear into students across the country as they experiment with nonlinear circuits and active components – making the course a prime breeding ground for threshold concepts.[48] Considering the course's characteristics, Scott and Harlow[49,50] postulated the existence of several threshold concepts within the experience: Thevenin's Theorem, dynamic resistance/linear approximation, phasors (including reactive power), feedback, and dependent sources. Considering the assertion that phasors and reactive power are proposed threshold concepts, it is perhaps surprising to see the lack of focus in work on alternating current (AC); rather, Carstensen & Bernhard[19] contend that authors are focused primarily on direct current (DC). Compared to an existing Electronics Concept Inventory,[51] the authors concluded that their identification of the threshold concepts aligned well except for reactive power, as it is usually more associated with Circuit Theory than Electronics. Recall, however, that the implication does not work in the reverse direction; just because a concept appears in a concept inventory does not mean that concept is a threshold concept.

Signal Processing / Controls

Within the realm of signal processing, analysis often departs the realm most familiar to students – called the time domain – in favor of a new world, the frequency domain. Accordingly, Carstensen & Bernhard[19,52] reported on the troublesome concept of the "frequency response." Likely first encountered when experimenting with the LaPlace Transform, another troublesome concept explored by González Sampayo,[47] students learn how to solve higher order differential equations of the form $P(D)y(t) = Q(D)x(t)$, for derivative operations $P(D)$ and $Q(D)$ and functions $x(t)$ and $y(t)$ by looking at the equation in a different light. The transform reframes the equation as an algebraic equation in a new variable s by which the solution is easily obtained; in fact, for a completely relaxed system (no initial conditions), the transform almost appears to amount to an innocent change of variables.

The new world of frequency is not trivial; in fact, the concept of "frequency response" is a difficulty when teaching circuits and controls. Two prominent methods of visualizing the frequency response exist, Bode Plots and Nyquist Diagrams. While both plots are created to analyze the frequency response, usually Bode Plots are taught due to the practical advantages they provide.[19] Bode Plots were investigated by Carstensen and Bernhard[19,52] under the investigation of frequency response as a "troublesome" concept. The language was hedged to avoid labeling frequency response as a threshold concept – intentionally or unintentionally.

Power and energy also pose a problem for students.[19] Although the distinction is the bane of physics teachers across the country, the title of "threshold concept" is not bestowed upon this relationship.

Electromagnetics

As a stepping stone to discuss signals in terms of communication, the topic of transmission lines arises in the typical electromagnetics course. A transmission line, like a coaxial cable, can be abstracted as the Lumped Element Model in terms of the functionality of familiar circuit elements like resistors, capacitors, and inductors. However, the analysis to talk about the so-called characteristic impedance of the transmission line and calculate the reactive power, arithmetic involving imaginary numbers – a threshold concept identified by Meyer and Land[2] is required. Reactive power *is* a postulated threshold concept in its own right;[50] therefore, Flanagan, Taylor, and Meyer[53] considered the concepts of reactive power in their investigation for teaching transmission lines.

Flanagan, Taylor, and Meyer[53] also argued that the concept of a field can easily be deemed a threshold concept when situated in the discussion of teaching transmission lines as Meyer and Land already justified the gravitational field as a threshold concept[2] - much of the rationale can be easily transferred.

While the concept of a field and reactive power – identified threshold concepts – appeared in the context of teaching transmission lines, the implications of addressing the embedded troublesome knowledge reaches far beyond electromagnetics. Since capacitors and inductors use an electric field and a magnetic field respectively to function, the plausible threshold concept (fields) is integrated throughout the Electrical Engineering curriculum (Figure 2).

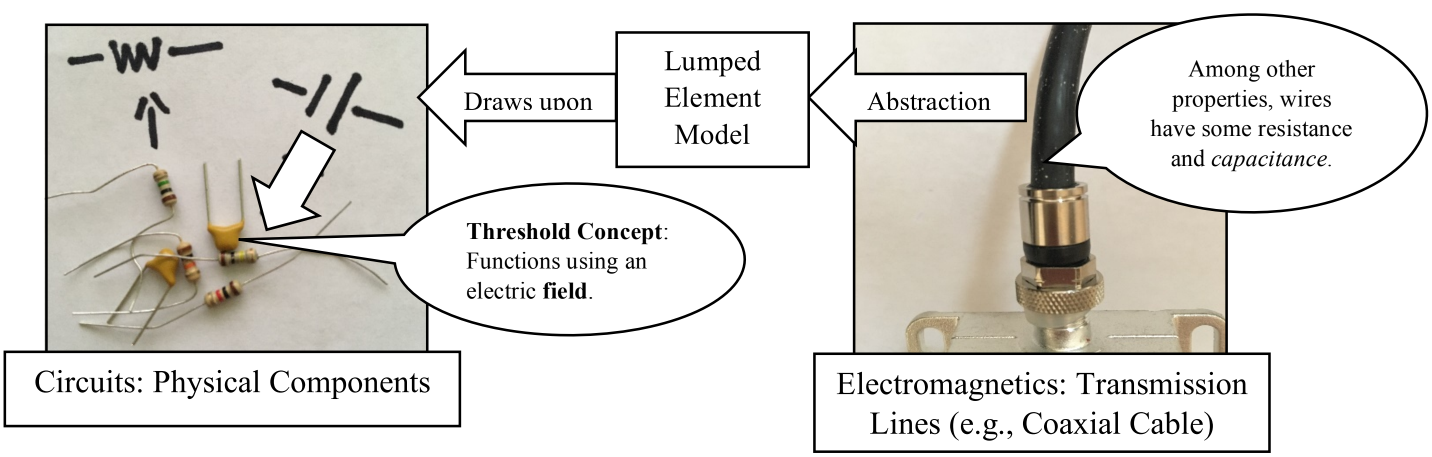

Figure 2: Integration of Threshold Concepts from Foundational Courses into the Later Years

Applying Threshold Concepts in Curriculum Development

Threshold concepts can be used as a framework for revising a curriculum.[4,20,54] While the curriculum is usually not as large as an entire discipline, work can be done on a course-by-course basis – then integrate as needed. Male & Baillie[4] offer the following suggestions for "curriculum renewal" (Figure 3).

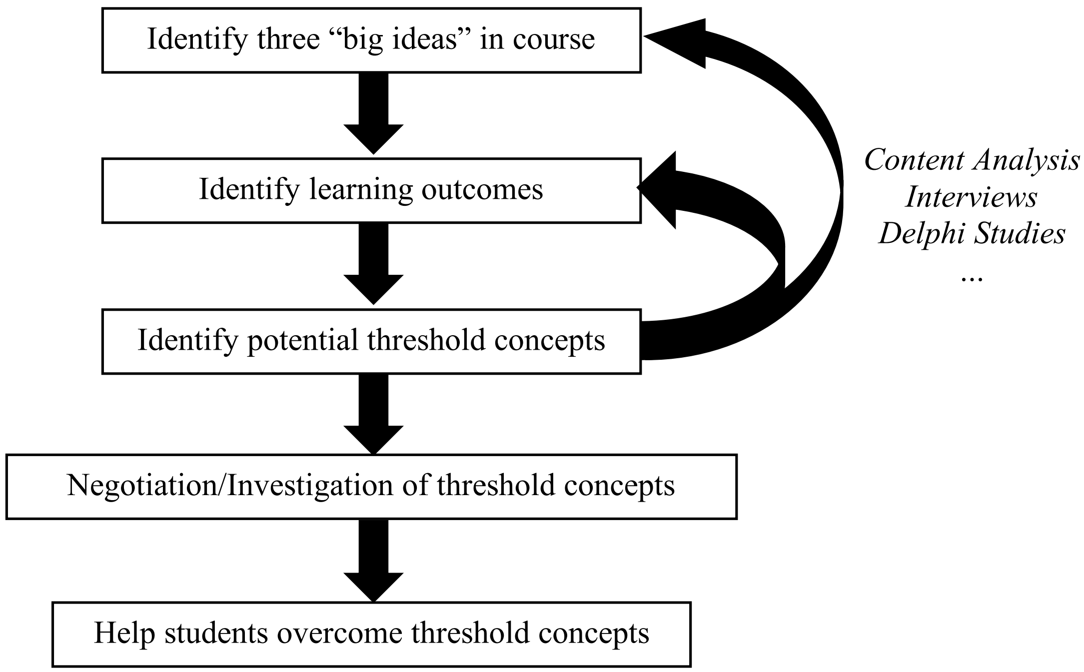

Figure 3: Using Threshold Concepts as a Framework for Curriculum Renewal

In the same way the "Fundamental Ideas"[40] organize Computer Science curricula around prevailing concepts in the discipline, curriculum renewal starts by identifying the big ideas in the discipline – Male and Baillie recommend three.[4] Once identified, check the learning objectives and begin applying the methods of identifying threshold concepts to massage the troublesome knowledge out of the core pieces of the curriculum. Naturally, not everyone will agree on the identification at first – thus, a vetting process begins as the concepts are negotiated and investigated. Finally, once consensus is reached, the curriculum is framed around the threshold concepts (whatever that may look like) and students are then guided through adding these ideas to their mental models. In-depth instructions for each step can be found in Male and Baillie.[4]

In fact, the only prominent use of threshold concepts as a manner of curricular renewal was reported by Male and Baille[20] and Parker and McGill[55] who designed their curriculum in a modular fashion. The remaining efforts appeared as pure research or as publications with pedagogical intent without a report to follow-up. To identify threshold concepts, multiple qualitative methods (focus groups at the university and at conferences in addition to interviews) were used as a means of triangulation – which is unique considering one method is typically used.

Due to the lack of literature in curriculum renewal, more research needs to be done as to what a complete overhaul of a curriculum looks like – preferably with detailed documentation – so this process can be seen in action for more than one context.

Bringing it Home: Threshold Concepts as a Tool for the RED Grant

Based on the literature, triangulation methods are needed to identify possible threshold concepts in the curriculum. Unlike the current breadth of literature, pinpointing areas of difficulty in the ECE curriculum tend to be framed purely as engineering education research. Few pieces detail the process of taking the threshold concepts and applying them in practice. Thus, the effort spurred by RED will be a prime example of research to practice. Moreover, to empower faculty in the significant restructuring of the ECE department, we intend to frame the investigation from a perspective of participatory design.

Situating Existing Methods in Participatory Design

Participatory design is research in its own right – an approach to design with the input of user involvement.[57] Spinuzzi[57] outlines the three basic stages of the design process: (1) initial exploration of work, (2) discovery process, and (3) prototyping. In the case of revolutionizing the ECE department, the primary stakeholders should have a voice and would be those involved in the participatory research: faculty, students, and industry. In fact, we are not only asking department stakeholders to identify sites of threshold concepts, but also to enroll them in a grass-roots, transformative effort. To that end, our survey of identifying threshold concepts provided an opportunity for dialog that can kick-start the culture shift of the department and map the movement to the three stages of the participatory design process.

Due to institution constraints for piloting classes, we focused on faculty. Shinners-Kennedy and Fincher's[33] suggested instrument, CoRe,[37] is especially useful as a tool for engaging faculty in self-reflection as it targets their PCK as opposed to their memories as an undergraduate student. Thus, faculty will be tasked with exploring the current landscape of the curriculum and how they provide their impact on student development. Next, those who complete the CoRe will convene in focus groups to discuss the future of the department in terms of five big ideas graduate must know/master when they leave the program and how faculty can aid the students in achieving those objectives along the way – each session will be audio recorded and transcribed. Finally, the transcriptions from the focus groups and CoRes will be analyzed using content analysis and coded with respect to the primary criteria for threshold concepts; that is, concepts will be culled if they are transformative and integrative – secondary characteristics will be used as proxies if the primary characteristics are not immediately obvious. The big ideas generated by the focus groups and the identified threshold concepts will be ranked and rated through a three round Delphi Study. Thus, the faculty will have collectively generated five big ideas for graduates to master and a set of threshold concepts by which the curriculum can be reshaped to better address their "troublesome" nature. The mapping is summarized in Table 2.

Table 2: Mapping the Proposed Methods to the Stages of Participatory Design

Participatory Design Stage	Method	Description
Initial exploration of work	CoRe	Engage faculty in a self-reflection on the curriculum and their contribution to student development.
Discovery process	Focus Group	Foster communication between faculty (guided by CoRe results) in the department to explore what students must know when they leave the program.
Prototyping	Delphi Study	Collaborate through structured conversation to prototype a set of threshold concepts in the curriculum and arrive at a consensus on five big ideas graduates must know/master.

Conclusion

We look forward to embarking on the journey of revitalizing the curriculum as powered by a collaborative movement comprised of faculty, students, and representatives from industry. We aim to transform both the traditional curriculum and culture of a large ECE department by invoking a new model of curricular change that is hoped to emphasize design and innovation such that students can choose from a variety of pathways to a degree. We are developing a combination of approaches to ensure disciplinary depth and a variety of learning experiences by employing a participatory design approach that engages faculty and students in industry. Through this ambitious project, we aim to increase the diversity of students entering the program, the variety of pathways through the program, and the kinds of careers graduates pursue.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. EEC-1623067. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References

1. Perkins, D. (2008). Beyond Understanding. *Threshold concepts within the disciplines*, 3-19.
2. Meyer, J., & Land, R. (2003). *Threshold concepts and troublesome knowledge: Linkages to ways of thinking and practising within the disciplines* (pp. 412-424). Edinburgh: University of Edinburgh.
3. Freire, P. (1970). The banking concept of education. *2004) Educational foundations: An anthology of critical readings*, 99-111.
4. Male, S. A., & Baillie, C. A. (2014). Research guided teaching practices: Engineering thresholds; an approach to curriculum renewal. *Cambridge handbook of engineering education research*, 393-408.
5. Ambrose, S. A., Bridges, M. W., DiPietro, M., Lovett, M. C., & Norman, M. K. (2010). *How learning works: Seven research-based principles for smart teaching*. John Wiley & Sons.
6. Lucas, U., & Mladenovic, R. (2007). The potential of threshold concepts: an emerging framework for educational research and practice. *London Review of Education*, *5*(3), 237-248.
7. Bandura, A., & Walters, R. H. (1977). Social learning theory.
8. Gauvain, M. (2008). Vygotsky's sociocultural theory.
9. Stets, J. E., & Burke, P. J. (2000). Identity theory and social identity theory. *Social psychology quarterly*, 224-237.
10. Tonso, K. Engineering Identity. Johri, A., & Olds, B. M. (Eds.). (2014). *Cambridge handbook of engineering education research*. (pp. 267-282). Cambridge University Press.
11. Gee, J. P. (2000). Identity as an analytic lens for research in education. *Review of research in education*, *25*, 99-125.
12. Newstetter, W. C., & Svinicki, M. D. (2014). Learning theories for engineering education practice. *Cambridge handbook of engineering education research*, 29-46.
13. Pellegrino, J. W., DiBello, L. V., & Brophy, S. P. (2014). The science and design of assessment in engineering education. *Cambridge handbook of engineering education research*, 571-598.
14. Rahman, M., & Ogunfunmi, T. (2010, May). A set of questions for a concept inventory for a DC Circuits course. In *Proceedings of 2010 IEEE International Symposium on Circuits and Systems* (pp. 2808-2811). IEEE.
15. Rowbottom, D. P. (2007). Demystifying threshold concepts. *Journal of Philosophy of Education*, *41*(2), 263-270.
16. Barradell, S. (2013). The identification of threshold concepts: a review of theoretical complexities and methodological challenges. *Higher Education*, *65*(2), 265-276. doi:10.1007/s10734-012-9542-3.
17. O'Donnell, R. (2010). A critique of the threshold concept hypothesis and its application to opportunity cost in economics. (Working Paper No. 164). Retrieved from http://www.finance.uts.edu.au/research/wpapers/wp164.html
18. Kiley, M. (2009). Identifying threshold concepts and proposing strategies to support doctoral candidates. *Innovations in Education and Teaching International*, *46*(3), 293-304.
19. Carstensen, A. K., & Bernhard, J. (2008). Threshold concepts and keys to the portal of understanding. R. Land, J. Meyer, & J. Smith (Eds.). *Threshold concepts within the disciplines*, 143-154. Rotterdam: Sense.
20. Male, S. A., & Baillie, C. A. (2011, September). Engineering threshold concepts. In *Proceedings of SEFI Annual Conference, Lisbon*.
21. Cousin, G. (2006). An introduction to threshold concepts.
22. Zander, C., Boustedt, J., Eckerdal, A., McCartney, R., Moström, J. E., Ratcliffe, M., & Sanders, K. (2008). Threshold concepts in computer science: A multi-national empirical investigation.
23. Davies, P. (2003). Threshold concepts: How can we recognise them? Embedding threshold concepts project: working paper 1.
24. Fonteyn, M. E., Kuipers, B., & Grobe, S. J. (1993). A description of think aloud method and protocol analysis. *Qualitative Health Research*, *3*(4), 430-441.
25. Nielsen, J., Clemmensen, T., & Yssing, C. (2002, October). Getting access to what goes on in people's heads?: reflections on the think-aloud technique. In *Proceedings of the second Nordic conference on Human-computer interaction* (pp. 101-110). ACM.
26. Carstensen, A. K., & Bernhard, J. (2012). Make links–Overcoming the threshold and entering the portal of understanding. In *Threshold concepts in practice, 4th Biennial International Threshold Concepts Conference, Dublin, 28-30 July, 2012.*

27. Marton, F., Tsui, A. B., Chik, P. P., Ko, P. Y., & Lo, M. L. (2004). *Classroom discourse and the space of learning*. Routledge.
28. Herman, G. L., & Loui, M. C. (2012, June), Identifying the Core Conceptual Framework of Digital Logic. *Paper presented at 2012 ASEE Annual Conference & Exposition*, San Antonio, Texas. https://peer.asee.org/21469
29. Linstone, H. A., & Turoff, M. (Eds.). (1975). *The Delphi method: Techniques and applications* (Vol. 29). Reading, MA: Addison-Wesley.
30. Passig, D. (1997). Imen-Delphi: A Delphi variant procedure for emergence. *Human Organization*, *56*(1), 53-63.
31. Passig, D., & Sharbat, A. (2004). The Imen- Delphi procedure in practice. *Systems Research and Behavioral Science*, *21*(2), 187-191.
32. Hsu, C. C., & Sandford, B. A. (2007). The Delphi technique: making sense of consensus. *Practical assessment, research & evaluation*, *12*(10), 1-8.
33. Shinners-Kennedy, D., & Fincher, S. A. (2013, August). Identifying threshold concepts: from dead end to a new direction. In *Proceedings of the ninth annual international ACM conference on International computing education research* (pp. 9-18). ACM.
34. Fischhoff, B., (1975). Hindsight is not equal to Foresight: The Effect of Outcome Knowledge on Judgment Under Uncertainty. Journal of Experimental Psychology: Human Perception and Performance, 1 (3): p. 288-299.
35. Fischhoff, B., (1982). For those condemned to study the past: Heuristics and biases in hindsight. *Judgement under uncertainty: heuristics and biases*, D. Kahneman, P. Slovic, and A. Tversky, Editors. Cambridge University Press: Cambridge.
36. Guilbault, R. L., Bryant, F. B., Brockway, J. H., & Posavac, E. J. (2004). A meta-analysis of research on hindsight bias. *Basic and Applied Social Psychology*, *26*(2-3), 103-117.
37. Loughran, J., Berry, A., & Mulhall, P. (2012). *Understanding and Developing ScienceTeachers' Pedagogical Content Knowledge* (Vol. 12). Springer Science & Business Media.
38. Shulman, L. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard educational review*, *57*(1), 1-23.
39. Eckerdal, A., McCartney, R., Moström, J. E., Ratcliffe, M., Sanders, K., & Zander, C. (2006, June). Putting threshold concepts into context in computer science education. In *ACM SIGCSE Bulletin* (Vol. 38, No. 3, pp. 103-107). ACM.
40. Schwill, A. (1994). Fundamental ideas of computer science. *Bulletin-European Association for Theoretical Computer Science*, *53*, 274-274.
41. Luker, P. A. (1994, March). There's more to OOP than syntax!. In *ACM SIGCSE Bulletin* (Vol. 26, No. 1, pp. 56-60). ACM.
42. Zander, C., Boustedt, J., McCartney, R., Moström, J. E., Sanders, K., & Thomas, L. (2009, August). Student transformations: are they computer scientists yet?. In *Proceedings of the fifth international workshop on Computing education research workshop* (pp. 129-140). ACM.
43. Shuman, L. J., Besterfield- Sacre, M., & McGourty, J. (2005). The ABET "professional skills"—Can they be taught? Can they be assessed?. *Journal of engineering education*, *94*(1), 41-55.
44. Coupey, E., Dorsa, E., Kemnitzer, R., McNair, L., & Martin, T. (2010, September). A Case Study of an Interdisciplinary Design Course for Pervasive Computing. In *Proc. Third Workshop on Pervasive Computing Education*.
45. McNair, L. D., Newswander, C., Boden, D., & Borrego, M. (2011). Student and faculty interdisciplinary identities in self- managed teams. *Journal of Engineering Education*, *100*(2), 374-396.
46. Carnes, M. T., & Diefes-Dux, H. A. (2013, June), *Conceptual Understanding of the Electrical Concepts of Voltage and Current: A Pilot Study of a Method to Create Representations of Students' Mental Models* Paper presented at 2013 ASEE Annual Conference & Exposition, Atlanta, Georgia. https://peer.asee.org/19339
47. González Sampayo, M. (2006). Engineering problem solving: The case of the Laplace transform as a difficulty in learning electric circuits and as a tool to solve real world problems. *Linköping Studies in Science and Technology Dissertation*, (1038).
48. Harlow, A., Scott, J., Peter, M., & Cowie, B. (2011). 'Getting stuck' in analogue electronics: threshold concepts as an explanatory model. *European Journal of Engineering Education*, 36(5), 435-447.

49. Scott, J., Harlow, A., Peter, M., & Cowie, B. (2010). Threshold concepts and introductory electronics. In *Proceedings of the 21st Annual Conference for the Australasian Association for Engineering Education* (p. 409). Engineers Australia.
50. Scott, J., & Harlow, A. (2012). Identification of threshold concepts involved in early electronics: Some new methods and results. *Australasian Journal of Engineering Education*, *18*(1), 61-68.
51. Simoni, M. F., Herniter, M. E. & Ferguson, B. A. (2004), “Concepts to Questions: Creating an Electronics Concept Inventory Exam”, Proceedings of the 2004 American Society for Engineering Education Annual Conference & Exposition, Session 1793.
52. Carstensen, A. K., & Bernhard, J. (2002). Bode Plots not only a tool of engineers, but also a key to facilitate students learning in electrical and control engineering. *Submitted to the Proceedings of PTEE2002 Physics Teaching in Engineering Education, Leuven*, 5-7.
53. Flanagan, M. T., Taylor, P. and Meyer, J.H.F. (2010). Compounded Thresholds in Electrical Engineering. 'Threshold Concepts and Transformational Learning' Meyer, J.H.F., Land, R., and Baillie, C., (eds), Sense Publishers, Rotterdam, 227−239.
54. Cousin, G. (2008). Threshold concepts: Old wine in new bottles or new forms of transactional curriculum inquiry. *Threshold concepts within the disciplines*, 261-272.
55. Parker, A., & Mcgill, D. (2016). Modular Approach and Innovations in an Engineering Program Design. In *Threshold Concepts in Practice* (pp. 179-193). SensePublishers.
56. Johnson, R. R. 1998. User-centered technology: A rhetorical theory for computers and other mundane artifacts. New York, NY: SUNY Press.
57. Spinuzzi, C. (2005). The methodology of participatory design. *Technical communication*, *52*(2), 163-174.