Developing a Framework for Identifying Threshold Concepts in Interdisciplinary Engineering Education: A Delphi Study in Cyber-Physical Systems

Abstract

This full methods paper explores the application of the Delphi method to identify threshold concepts in interdisciplinary settings within engineering education, focusing on the field of cyber-physical systems (CPS) as an intrinsic example. Threshold concepts represent transformative ideas that reshape learners' mental models and professional identities, often described as thinking and feeling like a professional in that discipline. However, identifying these concepts, particularly in interdisciplinary contexts like CPS, remains a challenge, considering these fields draw from several other distinct disciplines. In this paper, we review previous efforts using the Delphi method to identify threshold concepts across disciplines, outline our approach to the Delphi method in the interdisciplinary field of CPS as an example, and discuss how our method uncovered the challenges of identifying threshold concepts in an interdisciplinary context, including potential steps forward. By sharing lessons learned in implementing our Delphi processes, we contend that this approach to a Delphi study offers a framework for identifying potential threshold concepts in interdisciplinary subfields of engineering.

Introduction

Threshold concepts are transformative ideas that fundamentally change how learners engage with their disciplines, both cognitively and ontologically [1]. In engineering education, the transformation in cognition, identity, and practice is often described as *thinking more like an engineer* and *feeling more like an engineer* [2]. Although this way of thinking about fundamental knowledge in a field was proposed just over two decades ago, its identification and application are widely studied in single-disciplinary contexts [3]. Previous efforts have employed surveys, interviews, and one-minute papers [4-8] to explore threshold concepts across different disciplines. However, these approaches are often not enough to elicit potential threshold concepts, let alone for interdisciplinary fields.

Identifying threshold concepts has been met with methodological and conceptual challenges [9]. To illustrate, threshold concepts are typically studied in terms of features that define them, such as their *transformative* potential in terms of shifting a learner's cognition and identity. Prior research highlights that threshold concepts can exhibit a range of qualities, including transformative, integrative, bounded, discursive, and reconstitutive [10]. Each of these qualities is framed with different levels of negotiability, leading to a lack of consistency in the extent to which they are explored in identification-focused studies. Moreover, their *bounded* nature, meaning the concept is uniquely positioned inside a disciplinary area [1], [11], poses a particular issue in interdisciplinary contexts. Establishing that a concept is bounded requires defining knowledge and skills that are core to the field while recognizing intersections with other disciplines. Compounded by the variation in how students cross these thresholds and the lack of consensus on rigorous methods to identify these crossings, there is a consistent struggle to define *the* threshold concepts for a discipline – which is a more positivist perspective – instead of a range of potential thresholds that students might experience.

To address shortcomings in standard methodological tools, the Delphi method has been promoted as a promising mechanism for identifying threshold concepts, providing a structured process for gathering and refining expert opinions across multiple rounds of feedback [9]. The Delphi method is typically employed as a consensus-building technique where a panel of experts responds to multiple rounds of questionnaires, refining their feedback until consensus is reached [12]. This method has been applied in engineering education settings to develop the engineering education taxonomy of keywords [13], a classification scheme for first-year engineering courses [14], and, of particular relevance to this paper, proposing threshold concepts [15].

This paper presents the details of conducting a Delphi study to identify potential threshold concepts in the context of an interdisciplinary field, cyber-physical systems (CPS). A CPS is a system that combines physical and computational elements, broadly defined, and can encompass various applications in biology, telecommunication, and healthcare [16]. Through this Delphi study, we solicited and refined a list of core concepts in CPS, evaluated their alignment with threshold concept qualities, and gathered insights into the ways of thinking (or disciplinary perspectives) necessary for students to succeed in CPS. Unlike other Delphi studies used to identify threshold concepts, we first focused on identifying "core" concepts in CPS. We then probed panelists about whether the "core" concepts exhibited any of the threshold concept qualities using a series of guiding questions. In round two, we asked panelists to rate their agreement on the core concepts and rank them based on the extent to which they aligned threshold concept qualities. In the subsequent round, we encouraged participants to further frame the concepts in terms of ways of thinking to align more cohesively to the premise threshold concepts as transformative by highlighting specific disciplinary perspectives that encapsulate how CPS designers and engineers approach the field. We used this approach to limit the generation of broad concepts (e.g., frequency domain, differential equations) that are typically uninformative from a curricular (re)design perspective [17].

Research Aims

Our core contributions in this paper will involve (1) reviewing previous efforts using the Delphi method to identify threshold concepts across disciplines, (2) outlining our approach to the Delphi method for the interdisciplinary field of cyber-physical systems (CPS) in contrast to previous studies, and (3) reflecting on how our method uncovered the challenges of identifying threshold concepts in an interdisciplinary context.

Theoretical Framework

The study is grounded using the premise of *threshold concepts* [1]. Threshold concepts are described as gateways to a deeper and transformed understanding of the subject [2] and are often identified by a set of qualities that include [10]: *transformative*: the concept involves a shift in cognition and identity, *integrative*: the concept combines several distinct ideas, *troublesome*: the concept is difficult to learn, *bounded*: the concept is something unique to the field, distinguishing it from other distinct disciplines, *irreversible*: the concept is unlikely to be forgotten after learning, *discursive*: the concept provides an extended vocabulary, *reconstitutive*: the concept could involve rethinking their understanding of the field, addressing misconceptions. These characteristics, which are necessary to qualify an idea as a threshold concept, have shifted over the years. Accordingly, authors often select which qualities to investigate in their studies and discard the others for specific purposes of their studies [18]. Another essential quality of threshold concepts is liminality, which is linked to the troublesome quality of threshold concepts [19]. Once students are exposed to a threshold concept, they enter what is called the *liminal space,* a conceptual limbo of sorts where students gradually refine their understanding of the concept, which is often accompanied by uncertainty and discomfort. As Meyer and Land [19] explain, the experience of liminality is highly individualized; not all learners encounter the same ideas as threshold concepts, nor do they traverse the liminal space in the same way or timeframe. Liminality is exacerbated in interdisciplinary contexts because different disciplines may have fundamentally different ways of understanding and constructing knowledge [3].

Literature Review

Identifying Threshold Concepts

Over the years, various methods, including interviews, think-aloud protocols, and concept mapping, have been employed to identify threshold concepts [20]. Despite the wide range of approaches, the process of determining what ideas fit the qualities of threshold concepts has been rife with issues. Barradell [9] examined the challenges in identifying threshold concepts, particularly emphasizing the theoretical and methodological obstacles. One of the key challenges is the lack of consensus on how many characteristics a concept must possess to qualify as a threshold concept and the variability in interpretation across disciplines [9]. Beyond focusing on the number of relevant attributes for something to be a threshold concept, Quinlan et al. [18] also highlighted that participants' varied teaching experiences and disciplinary backgrounds can influence the concepts they identify as threshold concepts. In an attempt to resolve those issues, Barradell [9] suggested the Delphi method as a consensus methodology for achieving these objectives to better understand the perspectives of individuals and groups and reach an agreement on identifying the most salient threshold concepts.

The Delphi method, initially developed by Dalkey and Helmer [21], is a consensus-building technique in which a panel of experts engages in multiple rounds of iterative questionnaires that they complete independently, refining their feedback until a consensus is achieved [22]. After each round, responses are aggregated and anonymized, and the results are shared with the panel to refine in subsequent rounds via follow-up questions [23]. The Delphi method is built upon five core principles: (i) maintaining the anonymity of panel members, (ii) allowing iterative refinement of their judgments, (iii) providing controlled feedback through the presentation of aggregated responses from questionnaires, (iv) showcasing results from earlier rounds using measures of central tendency, and (v) achieving a consensus among experts [12].

Accordingly, several studies have identified threshold concepts within disciplines through Delphi studies, including those by Thomas et al. [24], Townsend et al. [25], and Kallia and Sentance [26], using a range of elicitation strategies. For example, Thomas et al. [22] used the method to establish threshold concepts for outdoor education in Australian universities. The study involved two rounds of consultation with a panel of academics, focusing on refining a draft list of threshold concepts and achieving theoretical saturation. Experts provided feedback on core ideas, which were iteratively revised by a facilitation team based on the panel's input. The consensus-building process centered around structured questions that encouraged reflection on the scope and focus of the concepts. Similarly, Townsend et al. [25] applied the Delphi method in the information literacy field, involving multiple rounds of feedback to identify and refine threshold concepts. The study required participants to review the literature on threshold concepts, provide feedback on a pre-existing list, and suggest additional ideas. Iterative rounds facilitated consensus, enabling participants to rank concepts based on strength and relevance to information literacy instruction. This structured process ensured the refinement of concepts while allowing panelists to adjust their views based on group feedback. In contrast, Kallia and Sentence [26] employed the Delphi method to explore computing teachers' perspectives on threshold concepts in programming. The study began with participants proposing potential threshold concepts and providing short descriptions. Subsequent rounds involved quantitative analysis of agreement levels, statistical feedback, and opportunities for panelists to revise their responses. The iterative design emphasized transparency and participant engagement, resulting in a refined list of threshold concepts for computing education.

Although these studies have successfully identified potential threshold concepts in their respective contexts, they often focus on individual disciplines. Moreover, there are limited examples of conducting Delphi studies to identify threshold concepts in general. Thus, the process for conducting such studies in an interdisciplinary context to identify threshold concepts remains unclear.

Challenges of Identifying Threshold Concepts in Interdisciplinary Fields
Correia et al. [27] emphasize that threshold concepts lack a fixed definition, making their identification highly subjective and discipline-dependent. This ambiguity aligns with the difficulty of identifying threshold concepts in interdisciplinary fields, which pose unique conceptual challenges in formulating threshold concepts due to their interplay among multiple disciplinary boundaries [3]. The merging of disciplines presents some philosophical issues when considering the concepts against the qualities outlined by Meyer and Land [1] as well. As Barradell and Fortune [11] highlight, *bounded* was frequently neglected in threshold concept studies, yet it is critical to establish what disciplinary practices are unique to a given field. In interdisciplinary fields like CPS, the *bounded* quality of threshold concepts becomes particularly salient. CPS combines knowledge from fields like engineering, computer science, and physical sciences [28], and this integrative nature often conflicts with the traditional understanding of *bounded*, as learners must navigate and synthesize diverse disciplinary perspectives.

Methodological challenges also arise in studying threshold concepts in interdisciplinary fields. Quinlan et al. [18] highlighted the difficulty of achieving consensus among experts from diverse disciplinary backgrounds, particularly when using methods like Delphi studies. Interdisciplinary fields inherently involve a diversity of expertise, which can lead to varied interpretations of core concepts [29]. This diversity complicates achieving consensus in an interdisciplinary context. Moreover, threshold concepts tend to be studied and presented with some degree of definitiveness – i.e., identifying *the* threshold concepts in a discipline. However, not all students will experience learning a supposed threshold concept in the same way, and asking someone to remember what it was like before fully grasping a concept in search of threshold concepts is fraught with hindsight bias [30]. Therefore, getting experts to agree on a common set of ideas using this theoretical framing can be arduous without intentionality in the research design.

Gaps and Opportunities
The challenges of identifying threshold concepts in an interdisciplinary field highlight the need for an approach that considers the integration of cross-disciplinary knowledge. Although

traditional Delphi studies have enabled researchers to identify potential threshold concepts in single-discipline contexts with varying levels of success, their application in interdisciplinary fields requires modifications to address the unique challenges. This study addresses the gap in identifying and exploring threshold concepts within interdisciplinary engineering education, focusing on CPS as an example. By reflecting on a Delphi study conducted in an interdisciplinary context, this research aims to refine the identification process of threshold concepts applicable to interdisciplinary subfields of engineering and computing.

An Example of a Delphi Study in an Interdisciplinary Context

Recruitment and Selection of Experts

Recruitment took place between February and April 2024. To ensure a diverse and representative panel of experts for the Delphi study, a two-pronged recruitment strategy was employed to obtain a range of perspectives from professionals with expertise in CPS. The recruitment process began with a screening survey using Microsoft Forms. The survey included key questions to assess participants' qualifications and relevance to the study, such as their working definition of CPS and professional experience in CPS-related projects. Links to the survey were shared through professional platforms and social media channels, targeting communities with a high concentration of CPS professionals, such as LinkedIn groups (e.g., ACM Members and Cyber Physical Systems). To supplement the broader recruitment through social media, we issued direct invitations to potential participants. Specifically, we contacted CPS researchers and practitioners from prominent research groups at U.S. higher education institutions. Our recruitment efforts yielded 11 experts in CPS and interdisciplinary engineering fields, including smart grid, autonomous systems, and machine learning – who participated in all three rounds of the study. The selected experts had extensive experience in interdisciplinary CPS research and practical applications and met the criteria necessary to make meaningful contributions. Expert participation was entirely voluntary, and written informed consent was acquired from every participant, as approved by the University of Cincinnati IRB (#2023-0362).

Data Collection

We administered questionnaires online, constituting a variant of the classical Delphi methodology, specifically an e-Delphi study [31]. In round one, participants first identified core concepts and then evaluated those concepts against the threshold concept characteristics using a series of guiding questions. In round two, we asked panelists to rate their agreement on the core concepts and select at least one concept they believed aligned with at least one of the threshold concept qualities. In the final round, we encouraged participants to elaborate on the concepts to pinpoint the threshold instead of discrete conglomerate topics. We collected the survey data through email between June and November 2024 for each round. Panelists provided written feedback independently in each round. There were no direct interactions or discussions between panelists during the entire process.

Round-by-Round Details

The data collection process was structured into three iterative rounds, adhering to the Delphi method's principles of achieving consensus through structured feedback and refinement [22]. The complete list of prompts for each round is in Appendix A.

Round 1

The first round of the Delphi study aimed to generate a comprehensive pool of potential threshold concepts in CPS. We invited experts to propose "big ideas" or foundational ways of thinking critical to understanding and mastering CPS, guided by open-ended prompts. Using the guiding questions, they were also asked to evaluate these concepts against the threshold concept characteristics—transformative, integrative, discursive, bounded, and reconstitutive [1]. Additionally, experts shared insights into their professional backgrounds and experiences, providing context for their responses.

Our questions were designed to avoid overwhelming participants with little to no experience with threshold concepts by miring them with jargon. In this case, we did not develop a prompt for *irreversible* and *troublesome*. In this context, we did not believe asking experts about concepts that are unlikely to be forgotten aligned with the purpose of this particular method; instead, it was better proxied by our prompt for *transformative* concerning how their thinking had changed about the CPS field. Moreover, when studying threshold concepts, the *troublesome* quality can (understandably) become the panacea for identification, causing participants to equate threshold concepts with difficult ideas and ignore other qualities. We still incorporated this aspect of a concept being difficult in the reconstitutive prompt, where participants reflected on misconceptions and when their views on a field were reevaluated.

Round 2

The primary goal of Round 2 was to refine the proposed core concepts identified in Round 1, continue evaluating their alignment with the five threshold concept qualities, and assess their significance in CPS. The participants were asked to rate their agreement on whether the proposed idea was essential to CPS. Each concept was rated on a 5-point Likert scale (1: Strongly Disagree, 5: Strongly Agree). Panelists could also indicate concepts they found unclear with a question mark ("?") and suggest breaking down overly broad ideas with an exclamation mark ("!"). Additional feedback was collected to refine vague or ambiguous concepts. In the second section, experts were asked to select at least one (up to five) proposed concepts from the list that they believe aligned with the qualities of each threshold concept.

Round 3

In Round 3, participants reviewed the aggregated results from Round 2, including the consensus levels for each concept. Additional questions invited participants to reconsider low-consensus concepts and identify any overlooked ideas. They were also tasked with framing the concepts in a way that more explicitly outlined the threshold that students must adopt to succeed in CPS and better align with the threshold concept framework.

The final survey presented the evaluation of the concepts in Round 2 based on levels of agreement among panelists. High-consensus concepts received at least 80% agreement. Experts were invited to comment on these concepts if further refinement or reconsideration was needed. Similarly, moderate-consensus concepts, with 50% to 79% agreement, were presented for confirmation or adjustment, and low-consensus concepts, receiving less than 50% agreement or a significant number of neutral responses, were reevaluated to determine whether they should be reframed, clarified, or excluded. In the last section of the survey, the panel evaluated the potential threshold concepts that received at least two votes across more than two threshold concept qualities. Experts were asked to distill the essence of these concepts into actionable ways of thinking that students must adopt to succeed in designing and implementing CPS. The panel also revisited threshold concepts that demonstrated lower alignment across the five threshold concept qualities examined. Experts were tasked with identifying three ways of thinking aligned with these concepts as a means to evaluate and refine the concepts with less alignment across threshold concept qualities.

Analysis

After Round 1, the participants' responses were synthesized to identify recurring concepts and group them into broader categories as appropriate based on the authors' disciplinary expertise. Each concept's alignment with the threshold concept characteristics was noted to inform the subsequent rounds. In Round 2, the majority of the survey was closed-ended to seek agreement on the potential core concepts generated in Round 1. We calculated agreement levels for each proposed concept based on participants' Likert-scale ratings as an average, percent agree (if the Likert score was 4 or 5), percent disagree (if the Likert score was 1 or 2), and percent neutral (if the Likert score was 3). Comments provided alongside ratings were used to refine concept formulations and identify areas of divergence.

For Round 3, the levels of agreement were recalculated based on the final round results to determine which concepts met a consensus level of at least 80%. The data from the open-ended responses were consolidated to form a list of the concepts as threshold ways of thinking determined by the participants. Low-consensus concepts were re-examined to understand underlying disagreements or contextual challenges. Moreover, we tallied the number of times each core concept was associated with a threshold concept quality.

Summary of Results

Round 1: Concept Identification and Categorization

The first round generated 65 core concept candidates for threshold concepts through expert responses to the open-ended questions. Each concept was reviewed and categorized based on its alignment with the five threshold qualities we considered. Descriptive statistics highlighted the distribution of expert marks across the qualities, with 47 potential threshold concepts explicitly identified in response to the open-ended questions.

Among the 65 concepts, seven were marked across all five threshold concept qualities based on our prompts, with "cybersecurity" garnering the most votes (i.e., 11 votes). Concepts such as "human-CPS interaction," "sensing and actuation," and "system integration and interoperability" were prominently represented in each of the five qualities. Additional concepts that participants associated with threshold concepts were sensing and actuation, sensor fusion, system control, and system modeling, but by only one panelist for a single quality across all five qualities for each concept.

A common issue with threshold concept research in engineering education emerged at this stage. When describing core concepts and associating them with threshold concept qualities, participants would often pitch broad ideas that combine multiple other smaller concepts [32]. For example, *optimization* was marked across all five qualities, receiving two marks in transformative, integrative, and discursive aspects. However, optimization as a concept bundles several other ideas within it, such as different techniques and types of optimization. Practically speaking, broad threshold concepts focused on content are typically not useful. Therefore, participants need to be prompted to break down larger ideas into their constituent parts.

Round 2: Refinement and Rating of Proposed Concepts

The second round employed a 5-point Likert scale to evaluate the proposed concepts. The experts rated the relevance of each concept as a foundational idea in CPS, and additional feedback was collected to refine vague or ambiguous concepts. The variability in expert ratings across the proposed concepts highlighted the diverse perspectives and interpretations within the CPS field. Although some concepts achieved strong consensus, others showed less agreement in ratings, indicating challenges in defining their relevance, applicability, or alignment with the core qualities of CPS. Concepts that span multiple domains (e.g., sensor fusion and machine learning) are inherently broad, making it difficult to delineate their boundaries within CPS. Accordingly, these concepts can face challenges in aligning with threshold concepts' “bounded” quality [11]. Experts may have also disagreed with these concepts' current applicability or significance in CPS education. For example, *CPSs need to use transparent algorithms (Explainable AI)* received only 25% agreement, possibly due to its emerging nature and lack of universal adoption. We sought further refinement in Round 3.

Round 3: Consensus and Frame to Ways of Thinking

The third round aimed to further refine the concepts identified earlier, framing them as perspectives or ways of thinking shaped by the characteristics of threshold concepts [10]. After the third round of evaluation, all 11 experts agreed that 12 concepts, with at least 80% consensus on each concept, identified in Round 2 are essential for understanding and analyzing CPS. They indicated no need to refine or reconsider the results. For moderate-consensus concepts in Round 2, 3 concepts achieved higher agreement levels in Round 3, and 3 concepts showed a decline or limited improvement in agreement. Twenty-eight concepts maintained their moderate-consensus status, with agreement levels stabilizing between 50%-79%. The low-consensus concepts in Round 2 were revisited in Round 3 to determine their potential inclusion or exclusion as core CPS ideas. Three concepts experienced notable increases in agreement, moving closer to moderate consensus, but ultimately did not reach at least 50% agreement.

The increase in high-consensus concepts demonstrates the ability of the expert panel to agree on the core concepts of the CPS as the Delphi process progressed [22]. This progress indicates the effectiveness of the iterative round in refining core concepts. However, many of the concepts remained in the moderate consensus range. Nonetheless, the high number of moderate consensus concepts emphasizes the diversity of perspectives and interpretations within the CPS interdisciplinary domain. The number of low-consensus concepts remained stable across rounds, suggesting that some perspectives may be too specialized, unclear, or irrelevant to CPS education and practice.

Discussion

As we conducted our Delphi study, it became more apparent that particular care is needed to address the challenge of the “bounded” quality in interdisciplinary fields like CPS while refining and contextualizing threshold concepts. Several panelists reflected on the difficulties of identifying threshold concepts in an interdisciplinary context. One expert observed: “*CPS, being interdisciplinary and complex, cannot be fully analyzed and studied by a handful of concepts. It* *will require expertise in various domains*." Another panelist highlighted: "*The problem is that CPS is naturally highly multi-disciplinary. How can we really form a community where people using completely different research languages understand each other and work together?*" These reflections emphasized the complexity of CPS as an interdisciplinary field and the challenges associated with achieving a consensus. We found this most evident in the large portion of concepts with moderate agreement across the panel.

Before beginning this research, our design was intentional with respect to presenting threshold concepts without alienating the participants with no educational research expertise, with each round including prompts that removed as much jargon as possible. Moreover, experts were also given opportunities to share their comments and feedback in each round. Instead of merely rating concepts on a 1 to 5 scale, panelists could also flag unclear concepts with a question mark ("?") or suggest breaking down broad ideas with an exclamation mark ("!"). We found these features to help process feedback from each round, allowing us to refine how concepts were presented for subsequent rounds. Still, our Delphi study was plagued initially by broad concepts that are not useful for curriculum development. Therefore, we found it necessary to push participants to expand on their proposed big ideas, pitching them as "ways of thinking" students must adopt to succeed in CPS design.

Advantages of Emphasizing Ways of Thinking
In the final section of Round 3, the experts reframed concepts that aligned with more than two threshold concept qualities and concepts with low alignment that were identified in Round 2. After summarizing and analyzing the ways of thinking identified by the experts, we found key examples in Appendix B, where the prompt to push experts to elaborate on the thresholds was related to the same thematic area.

When comparing the ways of thinking with at least two votes across multiple qualities related to threshold concepts, we should note the differences between high-alignment and low-alignment concepts using optimization as an example. Optimization was described as a holistic approach that requires balancing various constraints and trade-offs in high-alignment cases where concepts garnered multiple votes for threshold concept qualities. For instance, "mastering optimization involves understanding the need to balance various constraints and objectives, often leading to trade-offs rather than a single ideal solution," reflected an integrative and transformative approach to problem-solving. In contrast, low-alignment cases tended to emphasize procedural knowledge – for instance, "choosing optimal algorithms in terms of time and accuracy." Other low-alignment examples focused on broad topical areas rather than how CPS designers and engineers would approach problems in the field – for example, "students in this field need to master linear algebra, convex optimization, and design."

However, some phrasings of the potential threshold concepts seemed to garner more associations with the five qualities than others. One particular example with high alignment was the concept that "students must think holistically, recognizing the interplay between sensors, actuators, and computation, and understanding how individual components contribute to the overall behavior of the system." In contrast, the following concept exhibited lower alignment with the five qualities: "CPSs must be designed and analyzed in ways that recognize the interdependence of their components."This concept used a similarly structured statement but lacked specificity, which may have made it harder for panelists to recognize its alignment with threshold concept qualities. Although both statements refer to the idea of interdependence, the participants seemed to view these concepts differently. This divergence underscores the need to consider multiple perspectives continuously throughout the Delphi study; language appears to be a driver in how participants associate various ideas with threshold concept qualities – especially in interdisciplinary contexts.

Conclusion and Future Work

This methods paper reflected on a study about identifying threshold concepts in an interdisciplinary context through a Delphi study. By engaging a diverse panel of experts and iteratively refining the concepts based on threshold qualities in CPS, we highlighted the challenges of reaching a consensus on concepts unique to interdisciplinary contexts – especially regarding the bounded quality of threshold concepts. We show how a Delphi study could gradually push participants to expand upon the threshold at play in larger concepts – exposing the key thinking necessary for the discipline to be successful.

Although our approach addresses some of the methodological challenges inherent in researching threshold concepts in interdisciplinary subfields of engineering, further work is needed to explore how these concepts can be operationalized and taught effectively in classrooms. It has been argued that threshold concept research cannot only focus on analyzing the knowledge structure of a discipline, but we must also collect evidence of how students experience and ultimately learn these concepts [33]. Any threshold concepts identified through methods that only tap into the student experience or knowledge structure should be considered preliminary. Potential applications of threshold concepts in interdisciplinary engineering education include integrating them into curriculum design. Research-guided teaching practices suggest that threshold concepts can serve as focal points for curriculum renewal by structuring learning experiences around transformative ideas that shift students' cognitive frameworks. Although we are not quite at such a stage in engineering education, we get closer and closer to such applications as we continue to break down methodological barriers.

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Appendix A: Complete List of Prompts

Round 1 ---

Question 1
What are the big ideas or ways of thinking in cyber-physical systems (and related areas) that a student must master to engage in the field fully? Why are they essential? For example, a big idea in Calculus is the premise of a limit and how it can be used to define the derivative and the integral. List as many as you can think of; you will use your list in the upcoming questions.

Question 2
Please elaborate on how you developed the list for Question 1 to provide any necessary context for your answers. What kinds of CPSs did you consider when generating ideas, for example?

Instructions: *Using your response to the first questions, we will now explore your proposed big ideas and ways of thinking to uncover which ones could constitute* ***threshold concepts*** *for CPS. Threshold concepts are a relatively new educational theory that can guide curriculum development in higher education. However, they are tricky to identify in practice. Threshold concepts are said to have certain qualities that can be used as markers to identify them, so the following questions are intended to tap into those specific qualities. You may (and are encouraged to) add new ideas to your original list as you answer each question. Do not delete ideas from your original list; you may reconsider them as you address more questions.*

Transformative: One of the main qualities of a threshold concept is that it somehow transforms the individual. Researchers claim that when you fully learn something deemed to be a threshold concept, there is a shift in cognition and identity. Said more practically, if you are studying engineering, then fully understanding a threshold concept in that field would lead to you thinking more like an engineer and feeling more like an engineer.

Question 3
Transformative: One of the main qualities of a threshold concept is that it somehow transforms the individual. Researchers claim that when you fully learn something deemed to be a threshold concept, there is a shift in cognition and identity. Said more practically, if you are studying engineering, then fully understanding a threshold concept in that field would lead to you thinking more like an engineer and feeling more like an engineer.

What concepts in CPS (and related areas) changed how you think about these systems and the field? Why? Please share any personal experience(s) why learning these concepts had such an influence. The change in your thinking can be about how you design, build, or use the systems in your work.

Question 4
Integrative: Another typical feature is that the threshold concept "integrates" several ideas in the discipline by making connections between different concepts - especially unexpected

connections. For example, the Fundamental Theorem of Calculus is integrative because it connects derivatives (the mathematics concerning the rate of change and slopes of curves) and integrals (the mathematics concerning areas under curves) - two seemingly unrelated ideas. An integrative threshold concept provides a comprehensive or holistic understanding of a field, connecting various components or subfields into a unified framework.

What concepts in CPS (and related areas) have given you a holistic perspective of the field or connected many other ideas together? Why? Consider concepts that are pivotal in how you work with, study, or use these systems.

Question 5
Discursive: Another feature of threshold concepts is that they may provide an extended vocabulary such that the individual gains the ability to converse more fluently in the field. For example, learning the typical values of a quantity for something - such as processor speeds and capacitance - or abbreviations for common phrases - such as denial of service (DoS) or graphics processing unit (GPU) - is a simple way for newcomers to a field to be able to understand a disciplinary conversation more critically. Learning a threshold concept may translate to the individual being able to engage in discussions, explanations, and critical conversations related to complex concepts.

What challenges have you faced when explaining complex CPS concepts to others, especially those outside the field? Please explain how you typically address those challenges and share your strategies for making these concepts accessible to a broader audience.

Question 6
Bounded: A threshold concept is often described as an idea unique to a specific discipline that separates it from other fields. For example, the concept of "opportunity cost" (i.e., the loss of a potential gain when a person chooses one option over another, like choosing between job offers) is a classic example from economics well-situated in microeconomic theory. Being "bounded" goes beyond jargon like practitioners in machine learning calling input variables to a model "features" instead of "predictors." It can be difficult for a concept to be entirely based in a single field, especially for inherently interdisciplinary ones, so don't feel overly constrained here.

What concepts seem particularly unique to CPS instead of being shared between fields? Why?

Question 7
Reconstitutive: Finally, threshold concepts might make the individual rethink their understanding of other ideas in the field, especially misconceptions. So, fully understanding a threshold concept likely involves overcoming one or more misconceptions.

What concepts in CPS (and related areas) prompted you to reevaluate your fundamental understanding of the field or specific ideas in the field? Why? Elaborate if you believe a concept is tied to a misconception.

Round 2 --

Question 1
For each of the following, rate the extent you agree or disagree that the concept is a core concept or big idea in cyber-physical systems by marking an "x" in the appropriate column.

- 1 = Strongly *Disagree*, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly *Agree.*
- Mark an "x" in the ? column if you are unsure about the intention of the concept/big idea
- Mark an "x" in the ! column if you think the proposed concept or big idea could be broken down into a more specific concept (or set of concepts) and would prefer to rephrase it.
- Please feel free to add comments using Word's commenting features.

Question 2
If there are concepts not represented from our synthesis that you believe we missed, were not included in your original responses, or you would like to reformulate (your !'s from Q1), please identify them here.

Question 3
Next, like the previous round, we will backdrop your thoughts against the threshold concepts framework. We will start with transformative…
Transformative: One of the main qualities of a threshold concept is that it somehow transforms the individual. Researchers claim that when you fully learn something deemed to be a threshold concept, there is a shift in cognition and identity. Said more practically, if you are studying engineering, then fully understanding a threshold concept in that field would lead to you thinking more like an engineer and feeling more like an engineer.
Select at least one of (up to five) proposed concepts from the list in Q1 and Q2 that you believe fit this definition.

Question 4
Integrative: Another typical feature is that the threshold concept "integrates" several ideas in the discipline by making connections between different concepts - especially unexpected connections. For example, the Fundamental Theorem of Calculus is integrative because it connects derivatives (the mathematics concerning the rate of change and slopes of curves) and integrals (the mathematics concerning areas under curves) - two seemingly unrelated ideas. An integrative threshold concept provides a comprehensive or holistic understanding of a field, connecting various components or subfields into a unified framework.
Select at least one of (up to five) proposed concepts from the list in Q1 and Q2 that you believe fit this definition.

Question 5
Discursive: Another feature of threshold concepts is that they may provide an extended vocabulary such that the individual gains the ability to converse more fluently in the field. For example, learning the typical values of a quantity for something - such as processor speeds and capacitance - or abbreviations for common phrases - such as denial of service (DoS) or graphics processing unit (GPU) - is a simple way for newcomers to a field to be able to understand a disciplinary conversation more critically. Learning a threshold concept may translate to the individual being able to engage in discussions, explanations, and critical conversations related to complex concepts.
Select at least one of (up to five) proposed concepts from the list in Q1 and Q2 that you believe fit this definition.

Question 6
Bounded: A threshold concept is often described as an idea unique to a specific discipline that separates it from other fields. For example, the concept of "opportunity cost" (i.e., the loss of a potential gain when a person chooses one option over another, like choosing between job offers) is a classic example from economics well-situated in microeconomic theory. Being "bounded" goes beyond jargon like practitioners in machine learning calling input variables to a model "features" instead of "predictors." It can be difficult for a concept to be entirely based in a single field, especially for inherently interdisciplinary ones, so don't feel overly constrained here.
Select at least one of (up to five) proposed concepts from the list in Q1 and Q2 that you believe fit this definition.

Question 7
Reconstitutive: Finally, threshold concepts might make the individual rethink their understanding of other ideas in the field, especially misconceptions. So, fully understanding a threshold concept likely involves overcoming one or more misconceptions.
Select at least one of (up to five) proposed concepts from the list in Q1 and Q2 that you believe fit this definition.

Round 3 --

Question 1
In the previous round, there were some clarifications or extensions proposed by panelists about some of the proposed concepts. For each of the following, rate the extent you agree or disagree that the concept is a core concept or big idea in cyber-physical systems by marking an "x" in the appropriate column.

- 1 = Strongly *Disagree*, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly *Agree.*
- Mark an "x" in the ? column if you are unsure about the intention of the concept/big idea
- Mark an "x" in the ! column if you think the proposed concept or big idea could be broken down into a more specific concept (or set of concepts) and would prefer to rephrase it.
- Please feel free to add comments using Word's commenting features.

Question 2
If there are concepts not represented from our synthesis that you believe we missed, were not included in your original responses, or you would like to reformulate (your !'s from Q1), please identify them here.

Question 3
The following concepts had *very high* levels of agreement among panel members, meaning at least 80% of panelists agreed that the concept was core to CPS. Presented is the average agreement **(Avg)** using the scale of 1 = Strongly *Disagree*, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly *Agree.* **%D** is the proportion of panel members who strongly disagreed or disagreed the concept was core to CPS, **%N** is the proportion of panel members who neither agreed nor disagreed, **%A** is the proportion of panel members of agreed or strongly agreed the concept was core to CPS.
If you would like to comment on the results to refine or reconsider a concept or more than one concept as being core to CPS, please provide your reasoning below. If you have no comments, simply state *No comments*.

Question 4
The following concepts had *high* levels of agreement among panel members, meaning at least 50% but no more than 80% of panelists agreed that the concept was core to CPS.
In the empty space, confirm whether you agree with the concept being core to CPS by marking an X in that row.

Proposed Concept / Big Idea	Avg	%D	%N	%A	Agree
Concept you agree is core is to CPS					**x**
CPS design must recognize how the system interfaces with the real world	4.18	9%	18%	73%	

Question 5
The following concepts had mixed levels of agreement among panel members, meaning no more than 50% of panelists agreed that the concept was core to CPS with more than 20% marking neutral.
In the empty space, confirm whether you agree with the concept being core to CPS by marking an X in that row.

Proposed Concept / Big Idea	Avg	%D	%N	%A	Agree
Concept you agree is core is to CPS					**x**
Graphically mapping CPSs	3.45	18%	36%	45%	

Question 6
If there is a concept or concepts you would like to make a case for why they should or should not be considered core to CPS, please describe your reasoning here. If you have no comments, simply state *No comments*.

Next, we will overview the results regarding the threshold nature of the core concepts. Recall that threshold concepts are said to possess the following qualities:
Transformative: One of the main qualities of a threshold concept is that it somehow transforms the individual. Researchers claim that when you fully learn something deemed to be a threshold concept, there is a shift in cognition and identity. Said more practically, if you are studying engineering, then fully understanding a threshold concept in that field would lead to you thinking more like an engineer and feeling more like an engineer.
Integrative: Another typical feature is that the threshold concept "integrates" several ideas in the discipline by making connections between different concepts - especially unexpected connections. For example, the Fundamental Theorem of Calculus is integrative because it connects derivatives (the mathematics concerning the rate of change and slopes of curves) and integrals (the mathematics concerning areas under curves) - two seemingly unrelated ideas. An integrative threshold concept provides a comprehensive or holistic understanding of a field, connecting various components or subfields into a unified framework.
Discursive: Another feature of threshold concepts is that they may provide an extended vocabulary such that the individual gains the ability to converse more fluently in the field. For example, learning the typical values of a quantity for something - such as processor speeds and capacitance - or abbreviations for common phrases - such as denial of service (DoS) or graphics processing unit (GPU) - is a simple way for newcomers to a field to be able to understand a disciplinary conversation more critically. Learning a threshold concept may translate to the individual being able to engage in discussions, explanations, and critical conversations related to complex concepts.
Bounded: A threshold concept is often described as an idea unique to a specific discipline that separates it from other fields. For example, the concept of "opportunity cost" (i.e., the loss of a potential gain when a person chooses one option over another, like choosing between job offers) is a classic example from economics well-situated in microeconomic theory. Being "bounded" goes beyond jargon like practitioners in machine learning calling input variables to a model "features" instead of "predictors." It can be difficult for a concept to be entirely based in a single field, especially for inherently interdisciplinary ones, so don't feel overly constrained here.

Reconstitutive: Finally, threshold concepts might make the individual rethink their understanding of other ideas in the field, especially misconceptions. So, fully understanding a threshold concept likely involves overcoming one or more misconceptions.

Question 7
When ranking potential threshold concepts, the panel rated the following concepts with at least two votes across more than two qualities. However, some of them are somewhat broad and could be broken down a bit more to capture what about them makes them core to the CPS. In particular, we'd like to focus on what mindset or way of thinking a student needs to adopt to be successful in designing and implementing CPSs: for example, "Mastering optimization involves understanding the need to balance various constraints and objectives, often leading to trade-offs rather than a single ideal solution" and "Unlike modeling in purely physical or digital domains, CPS modeling requires a holistic approach to capture the interplay between sensors, actuators, and computational elements."

***Based on the concepts provided in this list*, if you were to summarize the three core ideas in CPS that most closely align with the threshold concept qualities, how would you describe those ways of thinking that students must adopt to be successful (like our provided examples)?**

Question 8
When ranking potential threshold concepts, the panel rated the following concepts with less alignment across threshold concept qualities.
***Based on the concepts provided in this list*, if you were to summarize the three core ideas in CPS that most closely align with the threshold concept qualities, how would you describe those ways of thinking that students must adopt to be successful (like our provided examples)?**

Question 9
Given the results we have presented from the panel, how do the results (i.e., core concepts and threshold concepts) align with your expectations based on your expertise and previous experiences?

Question 10
If you have any other comments or questions that were not covered in the previous prompts, please note them here

Appendix B

Key examples in elaborating on thresholds in Round 3

Thematic Area	Elaboration on threshold (High Alignment with Threshold Concept Qualities)	Elaboration on threshold (Low Alignment with Threshold Concept Qualities)
Optimization	"Mastering optimization involves understanding the need to balance various constraints and objectives, often leading to trade-offs rather than a single ideal solution."	"Choose optimal algorithms in terms of time and accuracy minimizing the difference between expected and actual performance." " Students in this field need to master linear algebra and convex optimization and design"
System Integration	"Students must think holistically, recognizing the interplay between sensors, actuators, and computation, understanding how individual components contribute to the system's overall behavior."	"CPSs must be designed and analyzed in ways that recognize the interdependence of their components. As CPS have both information network and physical network operating in sync, it should be planned keeping in mind the interaction and interdependence of both the networks."