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BOARD # 439: RETTL: Year One of Sizing Up Physical Computing to Explore Threshold Concepts in Cyber-Physical Systems

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RETTL: Year One of Sizing Up Physical Computing to Explore Threshold Concepts in Cyber-Physical Systems

Abstract

This paper outlines the Year 1 activities for a Research in Emerging Technologies for Teaching and Learning (RETTL) project about identifying threshold concepts in the field of cyber-physical systems (CPSs). Mastering threshold concepts, particularly in CPS design, leads to a transformed understanding of the subject and shifts students' identity within the context of the field. Given the cruciality of these concepts to a field, not just CPS, threshold concepts have been used to unpack student misconceptions and design the formative learning experiences necessary to master a subject's core ideas. In this project, we are developing a tabletop testbed for learning the core concepts in CPS design and using the system to identify which ideas constitute threshold concepts within the field. In Year 1, we created a prototype testbed and identified tentative threshold concepts using a Delphi study.

Context of the Project

From artificial pancreases to smart electricity grids, CPS embeds digital capabilities into our physical world [1]. This coupling motivates the concept of Industry 4.0 [2] and enables new tools for addressing mission-critical and safety-critical applications in energy, manufacturing, healthcare, and defense [3]. As CPS applications become more sophisticated and pervasive, it is becoming increasingly crucial to address emerging educational challenges for developing and maintaining a competitive CPS-capable U.S. workforce [4].

The past decade has seen significant advances in developing tools and curricula to provide students with formative CPS experiences [5]. However, despite these efforts, opportunities to study CPS are still limited [6], and most CPS curricula lack a unified treatment of the field's constituent topics [7,8]. Moreover, existing CPS learning tools—like the popular Arduino board—are designed primarily for single-user applications and thus offer limited opportunities for collaborative student interaction. Consequently, students increasingly engage with CPS in solitary—a trend deeply antithetical to real-world CPS design practice. These issues widen the participation gap [9,10], especially among underrepresented student groups, by reinforcing long-standing perceptions that cyber-informed fields are asocial [10].

Without a robust approach to foster more social and collaborative introductions to CPS education, would-be CPS students are disadvantaged considerably. There has been no synthesis of how CPS concepts and technologies can be made accessible in group settings, nor the concepts necessary for its mastery. Given that most entry-level engineering and computer science positions are filled by undergraduate students [8], new tools are needed at this level to provide meaningful exposure to CPS and to enrich collaborative learning within the CPS design process.

Research Questions

This research project seeks to uncover a new pathway for effectively educating undergraduate students about cyber-physical systems (CPSs). Specifically, the proposed project will leverage physical computing to facilitate collaborative introductions to CPS design and to identify CPS threshold concepts—concepts that, when mastered, represent a transformed understanding of CPS design. The results will lead to a new pathway for undergraduate students who will become aware of, interested in, and knowledgeable about CPS concepts, higher education programs, and careers. The proposed work also aims to uncover design principles that support a systematic, collaborative approach to CPS design and research

This project employs a two-pronged approach to investigate CPS design education and learning. The first thrust, the **Technology Innovation Thrust,** focuses on designing, developing, and evaluating a tabletop testbed we call CYber-PHysical systems Education & Research (CYPHER). CYPHER is a physical computing testbed intended to promote a social introduction to CPS design through collaborative play environments (Years 1 and 2). This testbed will be implemented in formal and informal learning settings to elicit and characterize student design strategies for CPS (Years 2 and 3).

The second thrust, the **Learning Innovation Thrust,** leverages the CYPHER testbed to explore the utility of threshold concepts as a theoretical framework for diagnosing and understanding the formative learning experiences necessary for students to master CPS design. This thrust will commence by identifying core concepts in CPS and potential threshold concepts to explore in future years of the project through a Delphi study (Year 1). Subsequently, the project will focus on creating model-eliciting activities (Year 2) and identifying threshold concepts specific to the field of CPS design (Year 3).

Our research questions in this project are as follows. Currently, we are focusing on and have results for **Learning Innovation Thrust RQ L1.**

Technology Innovation Thrust RQ1: How does the application of physical computing to CPS education support social and collaborative introductions to CPS design?
Technology Innovation Thrust RQ2: What are the distinguishing characteristics of designs generated using CYPHER, and how do student-generated CPS designs compare to those of design practitioners?
Learning Innovation Thrust RQ1: What are the key concepts involved in learning and mastering CPS?
Learning Innovation Thrust RQ2: What are the key characteristics of students' responses to an encounter with the existentially unfamiliar, educationally critical content of CPS design (i.e., threshold concepts)?

The anticipated outcomes of the technology thrust are a tangible user interface for problem-based learning and research, alongside identifying and formalizing a taxonomy of CPS design principles. On the other hand, the learning thrust aims to generate a preliminary CPS concept inventory based on threshold concepts as an assessment to complement teaching CPS theory and design. Toward this goal, the learning thrust seeks to identify potential threshold concepts within the field, ultimately informing the evaluation of learning and the design of more effective curricula.

Summary of Year One Activities

Technology Innovation Thrust. Significant progress was achieved in developing the CYPHER testbed, the core technological innovation of the project. The team first established conceptual and digital designs for the first prototype. This included defining system objectives, identifying necessary electrical components, and designing printed circuit boards (PCBs) for the physical, cyber, and network layers. Building on this foundation, the team coded initial device drivers for microprocessors and microchips on the PCBs, laying the groundwork for future functionalities. We are currently working on the second prototype, which is anticipated to be completed by the end of Summer 2025.

Learning Innovation Thrust. To identify *key concepts* in CPS, the learning thrust is based on the work of Meyer and Land's conceptualization of *threshold concepts*. The theory of threshold concepts originated in the context of a research project on teaching and learning in undergraduate education across disciplines in the United Kingdom [11]. It was developed more fully through Meyer and Land’s later writings [12–14], in which they articulated the defining characteristics of threshold concepts — particularly that they transform learners' thinking within a discipline and shape how learners identify as members of the disciplinary community. Defining threshold concepts can be instrumental in designing curricula at the undergraduate level across disciplines, including CPS. Therefore, we approached identifying the threshold concepts in CPS in two ways: a systematic literature review and a Delphi study.

Systematic Literature Review. We undertook a systematic literature review to understand what concepts across disciplines have been studied using the lens of threshold concepts. Because CPS is a highly interdisciplinary field and newer than the disciplines from which it is formed, direct searches for threshold concepts in this area were fruitless. Therefore, we explored potential threshold concepts in related fields, such as electrical engineering, computer engineering, computer science, cybersecurity, and systems engineering. Our search of papers from 2014 to 2024 across Education Research Complete, ACM Digital Library, and ASEE PEER resulted in only six papers meeting our search criteria. The proposed threshold concepts included abstraction, algorithmic complexity, performance analysis, procedural decomposition, and machine learning models [15]. This collection of concepts left much to be desired, signaling a gap in the literature with respect to threshold concepts at the heart of CPS.

Delphi Study. We launched a Delphi study in Summer 2024 to augment our findings in the systematic literature review. Delphi studies involve a panel of content experts curated by the researchers to engage in iterative questionnaires to elicit agreement among the panel about the topic of the study. Each iteration builds upon the results of one another until a consensus is reached in the group. The Delphi method has five foundational elements [16]: (i) anonymity of the panel members; (ii) iteration upon the judgments of the members; (iii) controlled feedback by the presentation of aggregated judgments from the questionnaire; (iv) presentation of the judgments from previous rounds using measures of central tendency; and (v) the formation of an expert consensus. The Delphi study concluded its third and final round in September. The Delphi study engaged 11 experts in CPS across disciplinary focus areas, including smart grid, autonomous vehicles, and machine learning.

Round 1 of the Delphi study aimed to generate a comprehensive pool of core concepts and potential threshold concepts in Cyber-Physical Systems (CPS). Experts were invited to propose core concepts or foundational ways of thinking critical to understanding and mastering CPS. After generating an initial list of core concepts, we presented guiding questions aligned with threshold concept qualities to further probe for core concepts while simultaneously identifying potential threshold concepts. The primary goal of Round 2 was to refine the proposed threshold concepts and core concepts identified in Round 1 by evaluating their alignment with the five threshold concept qualities and assessing their significance in CPS. Each concept was rated on a 5-point Likert scale (1: Strongly Disagree, 5: Strongly Agree) based on its relevance as a foundational concept in CPS. Additional feedback was collected to revise vague or ambiguous concepts. Then, experts were asked to select at least one (up to five) proposed concepts from the lists of core concepts that they believed strongly aligned with the threshold concept qualities. The third round of the Delphi study was designed to refine and finalize the core and potential threshold concepts identified in earlier rounds. 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 demonstrating lower alignment across the threshold concept qualities. Experts identified three ways of thinking aligned with these concepts to evaluate and refine those with less alignment across threshold qualities. Consensus was defined as a minimum threshold of 80% agreement on a given item.

Our preliminary results from the Delphi study suggest a wide range of core concepts, of which 58 were identified in Round 1, such as *cybersecurity*, *human-CPS interaction*, and *system integration*. Additional concepts were proposed in Round 2, bringing the total to 72 potential core concepts. Through further refinement in Round 3, only 15 of these concepts received at least 80% agreement, such as *CPS design must recognize how the system interfaces with the real world* and *methods for certifying safety critical CPSs.* Fifteen concepts were ultimately rejected with less than 50% agreement, leaving 28 concepts with mixed consensus (i.e., 50-79%). Only four concepts were collectively recognized by the panel as exhibiting all considered threshold concepts qualities: (1) *internet of things*, (2) *control systems*, (3) *sensor fusion is a complex process involving algorithms that must account for sensor errors, timing discrepancies, and data inconsistencies to improve overall system perception*, and (4) *dynamic programming*. We are currently processing these results in more detail.

Future Work and Conclusion

Our next steps in this project mainly concern the learning thrust, which involves creating a set of model-eliciting activities (MEAs) that can be deployed with the CYPHER testbed. An MEA is a problem-based learning approach to engage students in a long-term, realistic problem that allows space for students to self-assess their progress, document their work, reuse and share their model for other situations, and develop a working prototype. The problems are also open-ended to encourage a range of possible solutions [17]. We plan to test the MEAs with undergraduate engineering students and professional engineers to probe where threshold concepts might be at play using think-aloud interviews. Moreover, these interviews are intended to tap into what design strategies undergraduate students and CPS practitioners use when designing these kinds of systems. These interviews are intended to assist us with addressing our remaining research questions over the last two years of the project.

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