Work-in-Progress: A Systematic Literature Review of Exploring Threshold Concepts in Cyber-Physical Systems Education

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***Abstract* — This work-in-progress (WIP) research paper reports preliminary findings from a systematic literature review on proposed threshold concepts inherent to cyber-physical systems (CPS). The study aims to help instructors develop curricula for CPS applications by identifying concepts essential for students to master in its related fields. The guiding research question was: "What existing threshold concepts from related fields (e.g., computing, computer science, systems engineering) are applicable to CPS education?" We conducted a Systematic Literature Review (SLR) using three databases: Education Research Complete, ACM Digital Library, and ASEE PEER. Our initial query yielded 761 papers, and after filtering out duplicates and excluding those not meeting our inclusion criteria, six articles remained. We are continuing to search for threshold concepts in CPS-adjacent fields.**

Keywords—cyber-physical systems, threshold concepts, higher education, systematic review

I. Introduction

A cyber-physical system (CPS) refers to a new generation of physical, biological, and engineered systems that rely on computing and communication technologies to monitor, coordinate, control, and integrate their operations – such as autonomous vehicles and smart grid applications – which is crucial in developing technologies in the Industry 4.0 era [1]. As CPSs have become more widespread, addressing the emerging educational challenges of fostering a competitive workforce for designing and maintaining these systems is becoming salient [2]. Accordingly, as part of a larger NSF-funded project, we are developing a tabletop testbed to enable students to learn about the inner workings and design of CPSs. However, the core concepts undergirding these systems are drawn from several disciplines, and these concepts should be represented in any functional testbed aimed to promote learning in this field. This need motivated us to embark on a systematic literature review to take stock of what core concepts have been advanced in the educational literature within or tangential to CPS. To identify a workable set of concepts for engineering and computing education, we use the perspective of *threshold concepts*, a burgeoning framework for conceptualizing core ideas in a discipline or field from a curricular development perspective [3].

Threshold concepts are ideas that, once fully learned, are said to transform how a learner thinks and identifies within a discipline; in engineering, this is often described as *thinking like an engineer* and *feeling like an engineer* [4]. There is limited literature on core concepts in CPS due to its interdisciplinary and emergent nature; a smattering of publications exist on fundamental principles and ongoing challenges in the field (e.g., [5], [6], [7]) with some work describing curriculum development [8], [9]. In fact, Grimheden and Törngren [10] identify determining the core concepts of CPSs as an open question for the field.

Horváth and Gerritsen [6] outline 16 basic characteristics of CPSs that can provide a basis we might use as a starting point for identifying threshold concepts. Among these characteristics, the key descriptors are that CPSs can be open systems that change dynamically in terms of their boundaries and behaviors. They are hybrid systems with physical and cyber components that can operate on vastly different scales – both spatially and temporally – and employ different processes that ultimately combine to form the system's output, which may not be deterministic. As discussed by Ong et al. [1] and Liu et al. [7], a persistent challenge of CPSs is pattern abstraction, which results from physical and software limitations that cannot match the scale of some systems – security is also nontrivial. Moreover, Grimheden and Törngren [10] identify *synergy* as an idea core to CPS, based on the numerous definitions of CPSs that rely upon it, that is notably difficult to teach. In fact, they claim that "the expertise of the CPS engineer lies in the ability to understand and utilize this synergy – to differentiate from experts in the fields of computer science, control, communication etc" [10, p. 4]. However, this was not identified as a threshold concept – and it is possible that perspective has not yet permeated the CPS literature. Thus, we contend that a fruitful area to begin our work involves gathering threshold concepts in CPS-adjacent curricula to guide the development of CPS-focused curricula, which can help instructors make informed decisions about fundamental knowledge to impart to students [3].

II. Research Aims

This study aims to preliminarily identify threshold concepts in CPS-related fields that can inform CPS curriculum development. The collection of threshold concepts would then serve as a basis for further interrogation from an educational research perspective to determine the necessary learning

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outcomes for core concepts in CPS curricula. Thus, we posed the following exploratory research question: *What existing threshold concepts from related fields are applicable to CPS education?*

III. Theoretical Framework

Meyer and Land [11] define threshold concepts as "core ideas critical to students' progression" in learning a specific discipline [p. 4]. Accordingly, these concepts are described as gateways to a deeper and transformed understanding of the subject [4]. Threshold concepts are often identified by a set of fundamental qualities, which include some combination of the following [12]:

- *transformative*: involves a cognitive shift and shift in identity
- *integrative*: combines several ideas in the discipline that may not have appeared to be related
- *irreversible*: unlikely to be forgotten after learned
- *troublesome*: the concept may be challenging to learn (e.g., counter-intuitive)
- *bounded*: the concept establishes a boundary between disciplines, a concept that is uniquely positioned inside a disciplinary area

Over the years, definitions have been proposed that place different levels of flexibility on which qualities are indeed necessary [13], and authors often pick and choose which qualities to explore in their studies [14]. Other characteristics of threshold concepts have also been proposed, usually taking a decidedly secondary role. For example, threshold concepts are said to be *discursive*, meaning students require attaining new vocabulary to engage with the concept. Accordingly, identifying threshold concepts has been an ongoing concern in various fields of study [4], [15], [16], [17], [18].

Cousin [3] describes threshold concepts as "jewels in the curriculum" that "define potentially powerful transformative points in the student's learning experience" [p. 5]. Naturally, the literature suggests that these concepts could be used in curriculum development efforts [19]. Indeed, threshold concepts have been used to design curricula in engineering [19], [20]; for example, Parker and McGill [21] redesigned their undergraduate engineering program into modules that explicitly scaffold the learning of threshold concepts. Successful implementations like those documented in Parker and McGill suggest that we can accomplish a similar effort with CPS curricula.

IV. Methods

To address our research question, we conducted a systematic literature review (SLR), following Borrego et al. [22] and PRISMA guidelines [23], analyzing publications from the last decade (2014 – 2024). We chose this time frame because CPS is considered a crucial aspect of the fourth-generation industrial revolution (i.e., Industry 4.0) that gained popularity as a term in the 2010s. In fact, the number of studies conducted on CPS has continued to increase during the 2010s [24].

SLRs are a valuable tool used to assess and summarize existing research in various fields [22] and have been used to synthesize threshold concept research in other disciplines [25], [26]. They help to reduce barriers to accessing literature, provide a substantive critique of past research efforts, identify research gaps, and propose new directions for future studies [22].

A. Inclusion Criteria

To identify relevant studies, the first step was to determine the inclusion criteria that reflect the focus of the research question [22]. Our inclusion criteria for each source are listed below:

- IC1: Must include a discussion of threshold concepts from an educational perspective.
- IC2: Must focus on CPS or related fields.
- IC3: Must focus on higher education.
- IC4: Must be published between 2014 and 2024.
- IC5: Must be published in a conference or a journal

IC1 ensured that the source we reviewed was directly related to threshold concepts as they are conceptualized in education, meaning the paper discusses identifying or proposing possible threshold concepts students need to learn in a given field. To ensure relevance to the context of our research aims in higher education, we required the source to meet IC2 and IC3. The timeframe mentioned in IC4 ensured that the source provided a more current understanding of the field and its development. Finally, we ensured the source met the credibility criteria of IC5 by ensuring it came from recognized academic or professional platforms. We did not impose quality criteria at this stage because we are most interested in the proposed concepts and not whether they were studied with the most rigorous research design.

B. Database and Search Strategy

Our search for relevant articles involved reviewing the titles and abstracts of articles in three databases: Education Research Complete, ACM Digital Library, and ASEE PEER. We conducted this search in March 2024. We created a search string based on the intersection of threshold concepts and CPS, including related fields and applications:

> "Threshold Concept" AND ("Cyber-physical system" OR "Computer Science" OR "Computer Engineering" OR "Design" OR "Electrical engineering" OR "Cybersecurity" OR "Cybernetics" OR "Mechatronics" OR "Systems engineering" OR "Smart grid OR "Autonomous vehicle" OR "Artificial intelligence" OR "Human-computer interaction" OR "Engineering")

This query yielded 761 papers. After removing duplicates, 203 articles were excluded, leaving 558 articles for screening.

C. Screening Process

Figure 1 shows the PRISMA diagram for this systematic review [23]. We screened the titles and abstracts of the 558 articles and excluded 533 because they did not meet our inclusion criteria. These articles did not discuss threshold concepts from an educational perspective. They also did not focus on CPS or related fields. Another 19 articles were excluded based on the full text (IC1=8, IC2=7, IC3=4). Six articles ultimately fit all criteria.

D. Data Analysis

We conducted a full-text review of the remaining six articles to record the author, year of publication, country of study, methods used, theoretical or conceptual framework, threshold concepts explored, and selected results. In particular, we focused on extracting the proposed threshold concepts in this paper and aligning them with CPS qualities from Horváth and Gerritsen [6], a sampling of which is shown in Table I.

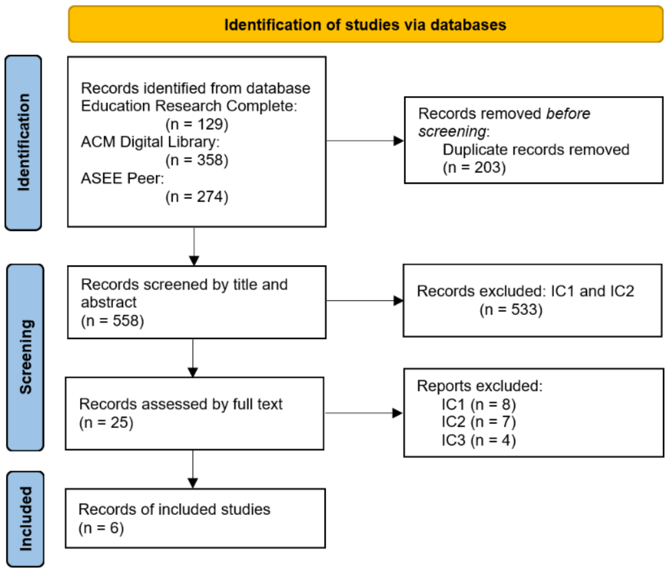

Fig. 1. Flowchart for articles, adapted from PRISMA [23].

E. *Limitations*

Our systematic literature review (SLR) has some limitations that must be acknowledged. First, we only considered conference and journal articles that were published in English in three databases: Education Research Complete, ACM Digital Library, and ASEE PEER. This means we might have missed other articles related to CPS applications that were not in the three databases. The systematic literature review also only focuses on works published between 2014 and 2024, which might result in ignoring some significant earlier studies that could offer insights into relevant threshold concepts. The date range can be expanded upon in the next steps of this research.

V. Findings

After conducting our SLR, we found no studies specifically discussing the threshold concepts present in CPS or its applications, like smart grid and autonomous vehicles. This suggests there is a considerable gap in the literature related to the study of these systems from this perspective. Furthermore, we found limited scholarship examining threshold concepts in CPS-related fields such as computing, computer science, and electrical engineering. The studies proposed threshold concepts in each field using a variety of methods for identifying them, such as surveys, interviews, and one-minute papers. We have organized the six articles into three categories: computing, computer science, and engineering.

A. *Threshold Concepts in Computing*

There is likely little doubt that designing and implementing CPSs requires competence in programming. One of the papers in our dataset, Sanders and McCartney [27], describes an analysis of the academic literature on computing education to identify the commonly discussed concepts that pose significant learning and transformational challenges for students. They reviewed the literature to determine which concepts had been discussed in computing as threshold concepts, similar to our goal here. They highlight a range of threshold concepts that have been identified in computing, of which we contend abstraction, modularity, and complexity (e.g., Big O notation), are most relevant to CPS. Abstraction (i.e., whether procedural as identified in [27], pattern, or in general) is a technique that helps manage complexity by focusing on high-level operations instead of low-level details and seems to be one of the most salient potential threshold concepts for us to consider. Because CPSs are hybrid systems with decision-making spread over several components in their network, students need to be able to leverage abstraction to model and design for the range of possible states the systems can exhibit.

As Ong et al. [1] and Liu et al. [7] describe, one of the challenges of cyber-physical systems is related to the scale and efficiency of CPSs, especially in terms of energy use. One of the overlaps in Sanders and McCartney's [27] review from the perspective of threshold concepts is complexity. Complexity refers to the framework for evaluating the efficiency and practicality of algorithmic solutions, such as Big O notation. Wherever possible, it is prudent for those designing CPSs to be concerned with optimization in different ways. Thus, it is likely that complexity is a candidate CPS threshold concept.

Next, Kallia and Sentence [28] conducted a Delphi study to reach a consensus among experienced educators and practitioners. The study involved multiple rounds of questionnaires where participants identified and rated the difficulty and significance of various potential threshold concepts in computing education, focusing on functions and procedural abstraction. The study identified 11 threshold concepts related to functions and procedural abstraction, where participants focused primarily on the troublesome characteristic of the concepts while balancing other threshold concept features, such as being integrative. The most relevant concepts were procedural decomposition and abstraction/modularity. The other concepts involve understanding the role of values in functions, how functions are called and executed, how program control flows, how data is passed to functions, how to break down problems using functions, how functions can call themselves, how data is sent back to the program, where variables can be accessed, and how function logic can be generalized. For CPS applications, we see the idea of abstraction and modularity reiterated, reinforcing our contentions based on Sanders and McCartney's [27] review.

Our last paper relevant to computing was Calver et al. [29], which identified essential concepts in an Introductory Numerical Analysis/Scientific Computing (NA/SC) course. Identifying threshold concepts involved conducting informal interviews with faculty members with extensive experience teaching the introductory NA/SC course. Based on the concepts suggested in the interviews, the authors performed an "intersection analysis" [p. 1] to identify common concepts repeatedly mentioned across different interviews. From the intersection analysis, four key threshold concepts were proposed for the introductory NA/SC course: 1) Error: understanding the role of error and controlling it; 2) Efficiency/Accuracy: choosing an algorithm that is optimal in terms of time and accuracy; 3) Numerical Software: refers to the choice and implementation of numerical methods through specific packages; and 4) Performance Analysis: investigation of algorithms and their implementations in software to study performance. The concepts identified appeared more fundamental to programming, and can be applicable to CPS.

B. *Threshold Concepts in Computer Science*

Horváth and Gerritsen [6] describe CPSs as having the ability for its "components [to be] able to memorize and learn from history and situations in an unsupervised manner," [p.22] so we should expect that concepts from machine learning and artificial intelligence to be relevant threshold concepts for CPS design and implementation. Allen et al. [30] explore the identification of threshold concepts in Artificial Intelligence (AI) education by employing a quick and minimally intrusive feedback method, called the One Minute Paper, to gather data on students' perceptions of their understanding and challenges during the course. Students were asked to share the topics they found most challenging and any unresolved questions they had. These concepts included the Support Vector Machine (SVM) technique, which is a powerful and versatile machine-learning model mainly used for classification tasks. The second concept was the Multilayer Perceptron (MLP), which is a class of feedforward artificial neural networks (ANN) that utilizes a backpropagation technique for training the network. Finally, Deep Learning Models were identified as a threshold concept, which are a subset of machine learning models that use multiple layers to extract higher-level features from raw input progressively. It is likely concepts in machine learning and artificial intelligence will need to be interrogated further; we are not yet certain what about them would qualify as thresholds.

Next, Alston et al. [31] conducted a study to explore how threshold concepts are identified and applied in web development education. They identified four main areas that students find challenging in web development, including basic programming principles, decomposition and abstraction, interface/content design, and anatomy of a web page. Many of these concepts have less bearing on CPSs because of the web development focus, except decomposition and abstraction.

C. *Threshold Concepts in Engineering*

In our last paper, Reeping et al. [32] conducted a systematic literature review on threshold concepts in electrical and computer engineering, drawing from chapters within a three-volume book series exclusively containing threshold concept literature, papers published in the ASEE annual conference and IEEE's Frontiers in Education conference, and publications found in Education Research Complete. What was found mostly concerned fundamental concepts like voltage and current and specific ideas from upper-division courses like Bode Plots and the Laplace Transform. When aligning these with Horváth and Gerritsen [6], the concepts reviewed do not appear to be particularly unique to CPSs.

VI. Conclusion and Future Work

Based on the preliminary findings from this systematic literature review on proposed threshold concepts within CPS-related fields, we found a workable set of potential threshold concepts that exist in related fields and linked them with the characteristics of CPS in Table 1 [1], [6]. However, considerable work must be done to verify that the qualities of threshold concepts apply to them, which is a persistent barrier in the threshold concept research [16], and more valuable springboards for curriculum development can be distilled by synthesizing them into ways of thinking and practicing [33].

There is still a debate about whether CPS is interdisciplinary, multidisciplinary, or transdisciplinary in nature [6]. This gap presents an opportunity for researchers to explore what core competencies are necessary to develop proficiency in designing these systems. Future work will involve expanding the literature review to include earlier publications and conducting a Delphi Study with CPS experts to explore the proposed threshold concepts further.

TABLE I. Identified Threshold Concepts in Related Fields

Proposed TCs	**Elaboration**	**Characteristics [6, p. 22]**
Abstraction (Procedural/ Pattern)	A technique that helps manage complexity by extracting the essential components of a problem or system.	"CPSs consist of a digital cyber-part and an analog physical-part, which are supposed to work together towards a high-level functional and structural strategy *and* CPSs are constructed of very diverse sets of components, which can enter and leave the collective at any time."
Complexity	Categorization of algorithms in terms of space use and runtime.	"CPSs, as well as their components, manifest on various extreme spatial scales and temporal ranges. Energy use and scalability are prime concerns *and* different sophisticated strategies are applied in order to manage resources and maintain security, integrity and reliability. "
Performance Analysis (Efficiency/ Accuracy/ Error)	Choosing an optimal algorithm in terms of time and accuracy that minimizes the difference between expected and actual performance.	
Procedural Decomposition and Design (Modulariza-tion)	Breaking down problems into smaller subproblems (e.g., using multiple smaller, self-contained functions)	"CPS is highly adaptive, capable of adjusting their functionalities to meet specific requirements or to respond to environmental changes *and* overall decision-making is distributed over a large number of components."
Support Vector Machine (SVM)	A powerful and versatile machine-learning model mainly used for classification tasks	"Components are able to memorize and learn from history and simulations in an unsupervised manner and to specialize themselves based on smart software agents and emergent intelligence *and* components are able to reorganize themselves in response to an unpredictable (emergent) system state or environmental circumstances."
Multilayer Perceptron (MLP)	A class of feedforward artificial neural networks (ANN) that utilizes a backpropagation technique for training the network	
Deep Learning Models	A subset of machine learning models, use multiple layers to extract higher-level features from raw input progressively	

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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.

VIII. References

[1] L. M. T. Ong, N. T. Nguyen, H. H. Luong, N. C. Tran, and H. X. Huynh, "Cyber Physical System: Achievements and challenges," in *Proceedings of the 4th International Conference on Machine Learning and Soft Computing*, in ICMLSC '20. New York, NY, USA:

Association for Computing Machinery, Mar. 2020, pp. 129–133. doi: 10.1145/3380688.3380695.

[2] M. Törngren, S. Bensalem, J. McDermid, R. Passerone, A. Sangiovanni-Vincentelli, and B. Schätz, “Education and training challenges in the era of Cyber-Physical Systems: beyond traditional engineering,” in *Proceedings of the WESE’15: Workshop on Embedded and Cyber-Physical Systems Education*, in WESE’15. New York, NY, USA: Association for Computing Machinery, Oct. 2015, pp. 1–5. doi: 10.1145/2832920.2832928.

[3] G. Cousin, “An introduction to threshold concepts,” *Planet*, vol. 17, no. 1, pp. 4–5, Dec. 2006, doi: 10.11120/plan.2006.00170004.

[4] S. Male and D. Bennett, “Threshold concepts in undergraduate engineering: Exploring engineering roles and value of learning,” *Australasian Journal of Engineering Education*, vol. 20, no. 1, pp. 59–69, Jan. 2015, doi: 10.7158/D14-006.2015.20.1.

[5] C. Zhang, X. Xu, and H. Chen, “Theoretical foundations and applications of cyber-physical systems: a literature review: Library Hi Tech,” *Library Hi Tech*, vol. 38, no. 1, pp. 95–104, Jan. 2020, doi: 10.1108/LHT-11-2017-0230.

[6] I. Horváth and B. H. M. Gerritsen, “Cyber-physical systems: Concepts, technologies and implementation principles,” presented at the Tools and Methods of Competitive Engineering, Karlsruhe, Germany, 2012.

[7] Y. Liu, Y. Peng, B. Wang, S. Yao, and Z. Liu, “Review on cyber-physical systems,” *IEEE/CAA Journal of Automatica Sinica*, vol. 4, no. 1, pp. 27–40, Jan. 2017, doi: 10.1109/JAS.2017.7510349.

[8] R. G. Helps and S. J. Pack, “Cyber-physical system concepts for IT students,” in *Proceedings of the 14th annual ACM SIGITE conference on Information technology education*, in SIGITE ’13. New York, NY, USA: Association for Computing Machinery, Oct. 2013, pp. 7–12. doi: 10.1145/2512276.2512303.

[9] A. M. K. Cheng, “An undergraduate cyber-physical systems course,” in *Proceedings of the 4th ACM SIGBED International Workshop on Design, Modeling, and Evaluation of Cyber-Physical Systems*, in CyPhy ’14. New York, NY, USA: Association for Computing Machinery, Apr. 2014, pp. 31–34. doi: 10.1145/2593458.2593464.

[10] M. E. Grimheden and M. Törngren, “Towards curricula for Cyber-Physical Systems,” in *Proceedings of the WESE’14: Workshop on Embedded and Cyber-Physical Systems Education*, in WESE’14. New York, NY, USA: Association for Computing Machinery, Oct. 2014, pp. 1–6. doi: 10.1145/2829957.2829965.

[11] J. Meyer and R. Land, “Threshold concepts and troublesome knowledge: Linkages to ways of thinking and practising within the disciplines,” 2003, Accessed: May 05, 2024. [Online]. Available: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=b98202852dc631ced19a98414cbd9e9461c10417

[12] J. H. F. Meyer and R. Land, “Threshold concepts and troublesome knowledge (2): Epistemological considerations and a conceptual framework for teaching and learning,” *High Educ*, vol. 49, no. 3, pp. 373–388, Apr. 2005, doi: 10.1007/s10734-004-6779-5.

[13] H. Salwén, “Threshold concepts, obstacles or scientific dead ends?,” *Teaching in Higher Education*, pp. 1–14, Jun. 2019, doi: 10.1080/13562517.2019.1632828.

[14] K. M. Quinlan, S. Male, C. Baillie, A. Stamboulis, J. Fill, and Z. Jaffer, “Methodological challenges in researching threshold concepts: a comparative analysis of three projects,” *High Educ*, vol. 66, no. 5, pp. 585–601, Nov. 2013, doi: 10.1007/s10734-013-9623-y.

[15] P. A. Crookes, P. A. Lewis, F. C. Else, and K. Crookes, “Current issues with the identification of threshold concepts in nursing,” *Nurse Education in Practice*, vol. 42, p. 102682, Jan. 2020, doi: 10.1016/j.nepr.2019.102682.

[16] D. Reeping, “Intersecting the Identification Problem and Mixed Methods Designs in Threshold Concept Research,” in *Threshold Concepts in the Moment*, J. P. Davies, E. Gironacci, S. McGowan, A. Nyamapfene, J. Rattray, A. M. Tierney, and A. S. Webb, Eds., Brill, 2024, pp. 43–57. doi: 10.1163/9789004680661.

[17] K. Nicola-Richmond, G. Pépin, H. Larkin, and C. Taylor, “Threshold concepts in higher education: a synthesis of the literature relating to measurement of threshold crossing,” *Higher Education Research & Development*, vol. 37, no. 1, pp. 101–114, Jan. 2018, doi: 10.1080/07294360.2017.1339181.

[18] S. Barradell, “The identification of threshold concepts: a review of theoretical complexities and methodological challenges,” *High Educ*, vol. 65, no. 2, pp. 265–276, Feb. 2013, doi:10.1007/s10734-012-9542-3.

[19] S. Male, C. Macnish, and C. Baillie, “Engaging students in engineering curriculum renewal using threshold concepts: 2012 8th International CDIO Conference,” *Proceedings of the 8th International CDIO Conference*, 2012.

[20] S. Male and D. Bennett, “Threshold concepts in undergraduate engineering: Exploring engineering roles and value of learning,” *Australasian Journal of Engineering Education*, vol. 20, no. 1, pp. 59–69, Jan. 2015, doi: 10.7158/D14-006.2015.20.1.

[21] A. Parker and D. McGill, “Modular Approach and Innovations in an Engineering Program Design,” in *Threshold Concepts in Practice*, R. Land, J. H. F. Meyer, and M. L. Flanagan, Eds., Brill, 2016, pp. 177–193. doi: 10.1163/9789463005128_015.

[22] M. Borrego, M. J. Foster, and J. E. Froyd, “Systematic Literature Reviews in Engineering Education and Other Developing Interdisciplinary Fields,” *J of Engineering Edu*, vol. 103, no. 1, pp. 45–76, Jan. 2014, doi: 10.1002/jee.20038.

[23] M. J. Page *et al.*, “The PRISMA 2020 statement: an updated guideline for reporting systematic reviews,” *BMJ*, vol. 372, p. n71, Mar. 2021, doi: 10.1136/bmj.n71.

[24] C. Jiang, Y. Ma, H. Chen, Y. Zheng, S. Gao, and S. Cheng, “Cyber physics system: a review: Library Hi Tech,” *Library Hi Tech*, vol. 38, no. 1, pp. 105–116, Jan. 2020, doi: 10.1108/LHT-11-2017-0256.

[25] H. Jones and L. Hammond, “Threshold concepts in medical education: A scoping review,” *Medical Education*, vol. 56, no. 10, pp. 983–993, 2022, doi: 10.1111/medu.14864.

[26] N. Nelson and R. Brennan, “Threshold concepts in the engineering educator’s journey: A systematic review,” *REES AAEE 2021 conference: Engineering Education Research Capability Development*, pp. 332–344, Mar. 2022, doi: 10.3316/informit.347536512344264.

[27] K. Sanders and R. McCartney, “Threshold concepts in computing: past, present, and future,” in *Proceedings of the 16th Koli Calling International Conference on Computing Education Research*, in Koli Calling ’16. New York, NY, USA: Association for Computing Machinery, Nov. 2016, pp. 91–100. doi: 10.1145/2999541.2999546.

[28] M. Kallia and S. Sentance, “Computing Teachers’ Perspectives on Threshold Concepts: Functions and Procedural Abstraction,” in *Proceedings of the 12th Workshop on Primary and Secondary Computing Education*, in WiPSCE ’17. New York, NY, USA: Association for Computing Machinery, Nov. 2017, pp. 15–24. doi: 10.1145/3137065.3137085.

[29] J. Calver, P. Muir, and T. Fairgrieve, “Improving Student Takeaway in an Introductory Numerical Analysis/Scientific Computing Course: A Threshold Concepts Approach,” in *Proceedings of the 21st Koli Calling International Conference on Computing Education Research*, in Koli Calling ’21. New York, NY, USA: Association for Computing Machinery, Nov. 2021, pp. 1–3. doi: 10.1145/3488042.3489971.

[30] B. Allen, M. Devlin, and A. S. McGough, “Using the One Minute Paper to Gain Insight into Potential Threshold Concepts in Artificial Intelligence Courses,” in *Proceedings of the 5th Conference on Computing Education Practice*, in CEP ’21. New York, NY, USA: Association for Computing Machinery, Jan. 2021, pp. 21–24. doi: 10.1145/3437914.3437974.

[31] P. Alston, D. Walsh, and G. Westhead, “Uncovering ‘Threshold Concepts’ in Web Development: An Instructor Perspective,” *ACM Trans. Comput. Educ.*, vol. 15, no. 1, p. 2:1-2:18, Mar. 2015, doi: 10.1145/2700513.

[32] D. Reeping *et al.*, “Board # 97 : How are Threshold Concepts Applied? A Review of the Literature,” presented at the 2017 ASEE Annual Conference & Exposition, Jun. 2017. Accessed: May 05, 2024. [Online]. Available: https://peer.asee.org/board-97-how-are-threshold-concepts-applied-a-review-of-the-literature

[33] D. Reeping, “Threshold concepts as ‘jewels of the curriculum’: rare as diamonds or plentiful as cubic zirconia?,” *International Journal for Academic Development*, vol. 25, no. 1, pp. 58–70, Jan. 2020, doi: 10.1080/1360144X.2019.1694934.