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From Algorithms to Understanding: The Role of Computational Thinking in Physics Education

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Abstract: This study investigates the integration of Computational Thinking (CT) in physics education over the past two decades (2003–2024) using a Systematic Literature Review (SLR) and bibliometric analysis. A total of 42 peer-reviewed articles from Scopus and PubMed databases were analyzed to identify trends, thematic developments, and geographic contributions. The findings reveal a significant growth in CT-related research after 2015, driven by global STEM education initiatives and advancements in digital tools. Notable contributions emerged from North America, Europe, and Asia, with three primary research themes: CT-based instructional methods and their impact on student outcomes, the role of computational tools and simulations in enhancing conceptual understanding, and frameworks for assessing CT competencies in physics curricula. While the findings highlight the transformative potential of CT in fostering problem-solving skills and bridging theoretical and practical learning, critical research gaps remain. These include the absence of standardized assessment methods, limited studies in underrepresented regions, and insufficient exploration of implementation strategies and teacher training. Addressing these gaps is essential to ensure equitable and effective CT integration across diverse educational contexts. This study underscores the interdisciplinary value of CT in preparing students for technology-driven challenges and provides actionable insights for researchers, educators, and policymakers to advance its application in physics education. By bridging theory and practice, CT can play a pivotal role in shaping future-ready learners equipped with critical, analytical, and computational skills.

Keywords: bibliometric analysis, computational thinking, physics education, SLR

Introduction

Computational Thinking (CT) is a problem-solving approach that involves the thought processes used in computer science to understand, design, and solve complex challenges (Angeli & Giannakos, 2020; Palts & Pedaste, 2020). This concept encompasses several core skills, including decomposition (breaking down large problems into smaller components), abstraction (identifying patterns or essential elements while ignoring irrelevant details), algorithms (developing systematic steps to achieve solutions), as well as evaluation and debugging (assessing the effectiveness of solutions and refining them when necessary) (Hunsaker, 2020). Although rooted in computer science, CT has expanded into

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various fields, including science, mathematics, and even the arts, due to its flexible and practical approach.

In the 21st century, CT has emerged as a fundamental skill essential for addressing the increasingly complex and technology-driven challenges of the modern world (Ojajuni, 2023; Roco, 2020). With the rapid advancement of digital technologies, the ability to think algorithmically, evaluate data, and formulate computational solutions has become increasingly relevant in everyday life and professional careers. Beyond its utility for programmers or computer scientists, CT enables individuals across disciplines to work more efficiently, think critically, and innovate in solving problems (Denning & Tedre, 2021). In the context of education, mastering CT is regarded as a pillar of digital literacy, alongside reading, writing, and numeracy. Consequently, integrating CT into various curricula, including physics, not only enriches students' understanding of scientific concepts but also prepares them to become lifelong learners and innovators in the future.

As the relevance of Computational Thinking (CT) continues to grow in the 21st century, it is crucial for students to develop these skills early as part of their preparation for navigating an increasingly complex and technology-driven world. CT is not merely a problem-solving approach but also shapes a systematic, critical, and adaptive mindset—abilities that form the foundation for success across various disciplines (Gale et al., 2022; Pérez, 2018). In education, CT plays a pivotal role in transforming how students comprehend, analyze, and solve problems through logical approaches applicable in diverse contexts.

For students, the ability to think computationally opens opportunities to understand abstract concepts through simpler models, identify patterns in data, and create effective and efficient solutions (Chen et al., 2024; Wang et al., 2023). This is particularly critical in fields like physics, where students often face challenges in integrating theoretical understanding with real-world applications. By incorporating CT into learning, students not only study science but also practice skills that train them to think like scientists or engineers.

Beyond academic benefits, CT equips students with competencies relevant to a constantly evolving job market (Hermans et al., 2024). By teaching students to think in algorithmic, data-driven, and innovative ways, they are better prepared to adapt to new technologies, grasp complex concepts, and collaborate in solving multidisciplinary problems. Thus, CT becomes not only a technical skill but also a framework for thinking that empowers students to become independent learners, innovators, and future leaders.

In the context of physics education, Computational Thinking (CT) holds significant potential to transform how students understand and learn complex and abstract scientific concepts. Through a CT-based approach, students can utilize computational tools and techniques to analyze physical phenomena, construct models, and solve problems in a more structured and efficient manner (Saad & Zainudin, 2024; Ye et al., 2023). CT enables students to develop critical skills such as decomposition, helping them break down large problems into smaller, manageable components, and abstraction, allowing them to focus on the essential elements of a problem while disregarding irrelevant details.

Integrating CT into physics education also provides opportunities to bridge the gap between theory and practice (Tschisgale et al., 2023). Students can use computer simulations, algorithms, or software tools to visualize concepts such as motion, energy, or electromagnetism, which might be challenging to grasp through traditional methods alone. By developing computational models, students not only understand the fundamental principles of physics but also learn how to test, evaluate, and refine their models, reflecting the scientific method in real-world practice.

As the importance of Computational Thinking (CT) in education, including physics learning, continues to grow, this research aims to uncover how CT trends have evolved in the context of physics education over the past two decades. Employing a Systematic Literature Review (SLR) and bibliometric analysis, this study focuses not only on identifying publication patterns and major contributions in the literature but also on evaluating how CT has been applied, examined, and integrated into physics education.

Another objective of this research is to review key findings from various related studies, assess the effectiveness of CT-based approaches in enhancing the understanding of physics concepts, and identify emerging challenges and opportunities. By analyzing relevant literature, this study seeks to provide in-depth insights into how CT approaches have aided students in not only grasping physics conceptually but also honing their critical, analytical, and computational thinking skills.

Methods

This study employs a Systematic Literature Review (SLR) and bibliometric analysis to evaluate the development and application of Computational Thinking (CT) in physics education over the past two decades. The SLR approach was chosen as it enables researchers to systematically identify, evaluate, and synthesize relevant literature, providing a comprehensive overview of research trends and key contributions to the field (Marzi et al., 2024; Paul et al., 2021). Bibliometric analysis complements the SLR by highlighting publication patterns, author collaborations, and emerging areas within the literature.

Literature Identification

Relevant literature for this study was systematically identified using Scopus and PubMed, two prominent academic databases known for their extensive indexing of peer-reviewed journals. The search focused on articles published between 2003 and 2024, using the keywords "computational thinking" and "physics education", combined with Boolean operators to refine the results. Inclusion criteria were set to select articles published in peer-reviewed journals, explicitly addressing the application or study of Computational Thinking (CT) in physics education. Additionally, only articles available in full-text and written in English were included, while duplicates and irrelevant studies were excluded. This approach ensured a high-quality selection of studies relevant to the integration of CT in physics education.

The search process involved two stages: a preliminary screening of titles and abstracts to eliminate irrelevant articles, followed by a full-text review to confirm eligibility based on the inclusion criteria. The results from both databases were cross-checked, and duplicates were removed. The selection process was systematically documented using a PRISMA flow diagram, highlighting the number of studies retrieved, screened, and included in the final analysis. This rigorous process resulted in a curated collection of studies that serve as the foundation for exploring trends, methodologies, and applications of CT in physics education. These studies provide valuable insights into how CT has been utilized to enhance students' understanding and engagement in learning physics.

Literature Selection

The selection process for this study was conducted in two distinct stages to ensure the relevance and quality of the included articles. The first stage involved screening the titles and abstracts of all retrieved articles to evaluate their preliminary relevance to the research objectives. Articles that explicitly mentioned Computational Thinking (CT) and its application in physics education were prioritized. This stage allowed the removal of articles that were tangential to the study or did not meet the inclusion criteria, such as studies focused solely on general computational methods or non-educational contexts.

In the second stage, articles that passed the initial screening underwent a detailed full-text review. This step was crucial to confirm that the studies met all predefined inclusion criteria, including publication in peer-reviewed journals, explicit relevance to the integration of CT in physics education, and methodological rigor. During this stage, key data were extracted from each article, including the author(s), year of publication, research objectives, methodologies used, and significant findings. This systematic process ensured that only high-quality and contextually relevant studies were included, forming a robust foundation for further analysis and synthesis of trends, strategies, and outcomes in the use of CT within physics education.

Bibliometric Analysis

The selected articles were analyzed using VOSviewer and the R programming language, leveraging their robust capabilities for bibliometric analysis and data visualization. VOSviewer was employed to map and visualize patterns of author collaborations, co-authorship networks, and keyword co-occurrence, providing a graphical representation of relationships and trends within the literature. This tool enabled the identification of influential authors, frequently explored themes, and emerging areas of research in the application of Computational Thinking (CT) in physics education.

Simultaneously, the Bibliometrix package in R was used to perform advanced bibliometric analyses, including trend analysis of publication outputs over time and citation network evaluations. This quantitative approach complemented the visual insights provided by VOSviewer, offering deeper statistical analyses of research impact and thematic evolution. Together, these tools provided a comprehensive understanding of the development and dissemination of CT-related research in physics education, highlighting key contributors, thematic clusters, and gaps in the current literature.

Synthesis and Analysis of Findings

The final set of selected articles was qualitatively analyzed to identify patterns and key themes, such as strategies for integrating CT into physics education, the effectiveness of CT-based approaches, and the challenges and opportunities associated with implementation. The data were synthesized to address the research questions and identify gaps in the existing literature.

Quality Evaluation

To ensure the validity and reliability of the findings, each selected article was systematically evaluated using the PRISMA framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). This framework provided a structured approach to assess the methodological rigor, clarity, and relevance of the studies to the research objectives. The evaluation process focused on ensuring that the included articles adhered to high standards of academic quality, including the explicitness of research objectives, appropriateness of methodologies, and transparency of results.

The PRISMA framework facilitated the documentation of the article selection process, from initial identification to final inclusion (Page et al., 2021). This involved a detailed review of study designs, data collection methods, and the validity of reported findings. The consistent application of PRISMA ensured that only studies meeting stringent criteria were included in the analysis, thereby strengthening the robustness and credibility of the research outcomes. This rigorous evaluation also helped identify potential biases, enhancing the reliability of insights derived from the reviewed literature.

Results and Discussion

For the purpose of this study, the authors selected a total of 42 relevant publications obtained from two prominent academic databases, Scopus and PubMed, following a comprehensive search process. These articles were published between 2003 and 2024 and were filtered using specific inclusion criteria, ensuring their relevance to the topic of Computational Thinking in Physics Education. The publications included 40 articles from Scopus and 2 articles from PubMed, all of which align closely with the study's objectives.

It is worth noting that the selected articles were published in highly regarded, peer-reviewed journals indexed by Scopus and PubMed. This ensures that the articles represent high-quality research in the field. The selection process focused on articles with a clear emphasis on integrating computational thinking into physics education, and the final dataset provides a robust foundation for exploring the trends, challenges, and opportunities in this interdisciplinary area of study.

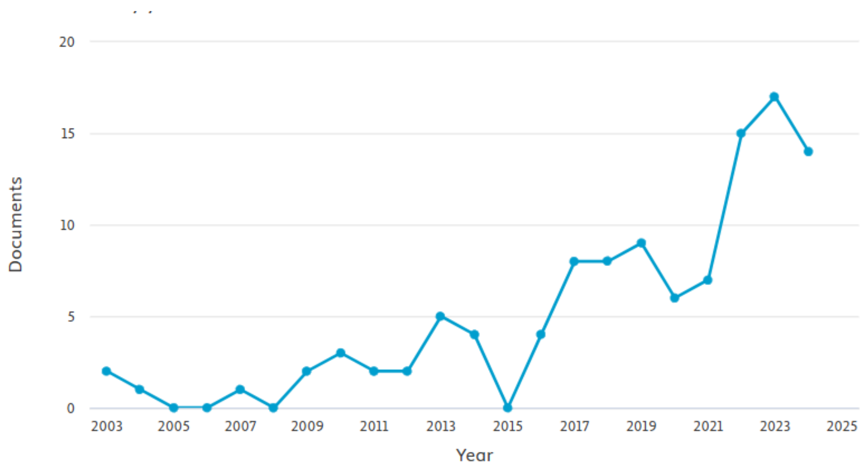

Figure 1. Annual Distribution of Publications on Computational Thinking in Physics Education (2003–2024)

The graph illustrates the annual distribution of publications related to Computational Thinking in Physics Education from 2003 to 2024. The data shows a gradual increase in research activity over the years, with a notable growth trend starting around 2015. Prior to 2015, the number of publications remained relatively low, typically fewer than 5 articles per year, indicating limited research focus on this topic during the early years.

From 2016 onward, a significant upward trend is observed, with a sharp increase in the number of publications between 2020 and 2023, peaking in 2023 with over 15 documents published. This surge reflects a growing interest in the integration of computational thinking in physics education, likely driven by advancements in digital tools and an increasing emphasis on computational skills in education (Angraini et al., 2024). The slight dip in 2024 might be attributed to the incomplete data for that year at the time of analysis. Overall, the graph underscores the increasing recognition of computational thinking as a critical component of modern physics education research.

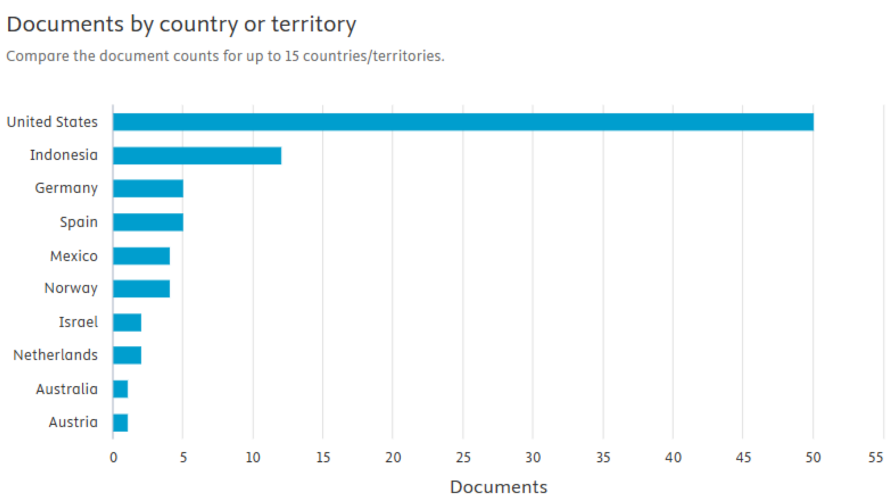

Figure 2. Documents by Country or Territory on Computational Thinking in Physics Education

Figure 2 presents the distribution of documents related to Computational Thinking in Physics Education by country or territory. The United States dominates the publication landscape with nearly 50 documents, highlighting its leading role in this area of research. Indonesia ranks second with a substantial contribution, publishing around 20 documents, reflecting the country's growing focus on integrating computational thinking into physics education.

Countries such as Germany, Spain, Mexico, and Norway contribute modestly, each publishing between 5 and 10 documents. Other nations, including Israel, Netherlands, Australia, and Austria, have fewer than 5 publications, indicating limited but notable participation in this research domain. This distribution underscores the global interest in computational thinking in physics education while highlighting significant disparities in publication activity across different countries.

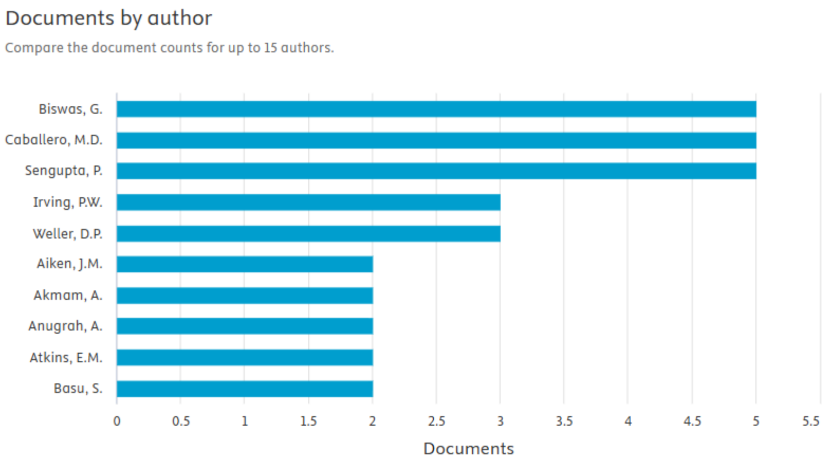

Figure 3. Top Authors Contributing to Computational Thinking in Physics Education Research

Figure 3 displays the top authors contributing to research on Computational Thinking in Physics Education, measured by the number of documents they have published. Authors such as Biswas, G., Caballero, M.D., Sengupta, P., and Irving, P.W. are prominent contributors, each with over four publications in this domain. Their frequent contributions indicate their central role in advancing this field of study.

Other notable authors, including Weller, D.P., Aiken, J.M., and Anugrah, A., have also made significant contributions, with each publishing multiple articles. This distribution reflects a collaborative research environment where a small number of authors drive a substantial portion of the literature, emphasizing their influence in shaping the discourse on computational thinking and its applications in physics education. The breadth of contributions from these authors highlights the growing interest and importance of this interdisciplinary research area.

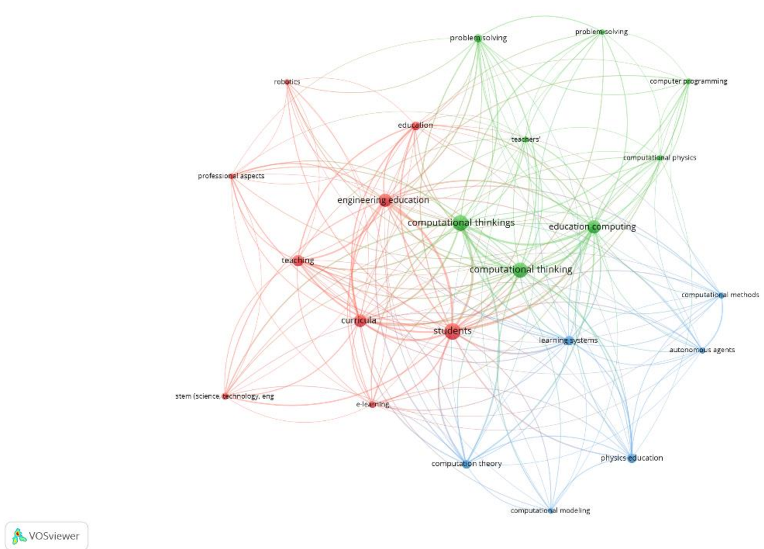

Figure 3. Keyword Co-Occurrence Network for Computational Thinking in Physics Education

The network visualization represents the co-occurrence of keywords in research articles related to Computational Thinking in Physics Education, generated using VOSviewer. The nodes in the graph represent keywords, and their size reflects the frequency of occurrence. Keywords that frequently appear together are connected by lines, forming clusters that indicate thematic areas of research.

The network visualization highlights the thematic connections within research on Computational Thinking in Physics Education, represented by distinct color-coded clusters. Each cluster groups closely related keywords, reflecting major areas of focus in the field (Dai et al., 2020). The green cluster, centered around keywords like computational thinking, problem-solving, and education computing, emphasizes the use of computational thinking as a pedagogical framework. This cluster showcases the role of computational thinking in enhancing problem-solving skills, computer programming abilities, and its applications in computational physics.

The red cluster focuses on pedagogical development, featuring keywords like teaching, engineering education, robotics, and curricula. This cluster highlights the integration of computational thinking into education, particularly in STEM and professional training contexts. It underscores efforts to develop curricula and teaching methods that incorporate computational tools and hands-on learning approaches, such as robotics.

Meanwhile, the blue cluster explores the application of computational thinking in physics education, with keywords like physics education, computational modeling, and learning systems. This cluster demonstrates the importance of computational tools and simulations in making abstract physics concepts more accessible and engaging for learners. The strong connections between clusters reflect the interdisciplinary nature of computational thinking, bridging education, STEM fields, and physics-specific applications. This interconnectedness points to opportunities for further cross-disciplinary research and collaboration.

This visualization reveals the interdisciplinary nature of computational thinking research, bridging education, engineering, and physics. The dense connections between keywords suggest a highly interconnected research landscape, with "computational thinking" serving as the central theme linking diverse domains. This network helps identify major focus areas and potential gaps in the existing literature.

Discussion

The findings from this study reveal several critical insights into the integration of Computational Thinking (CT) in physics education over the past two decades. The increasing number of publications, particularly after 2015, underscores the growing recognition of CT as a key component of modern education. This surge is likely driven by global initiatives promoting STEM education and the increasing emphasis on digital skills in the 21st century (Carabregu-Vokshi et al., 2024; Rahimi & Oh, 2024). The bibliometric analysis identifies three dominant research clusters: CT-based instructional methods, the use of computational tools to enhance conceptual understanding, and frameworks for assessing CT competencies. These clusters highlight the multifaceted nature of CT, bridging theoretical, practical, and assessment-based perspectives in education.

Despite this growth, the study highlights critical gaps that need to be addressed. The lack of standardized methods for assessing CT competencies poses challenges in evaluating student outcomes consistently (Lucey et al., 2020). Furthermore, there is limited research exploring the implementation of CT in diverse educational contexts, particularly in underrepresented regions or less resource-intensive settings. This gap suggests the need for more inclusive studies that account for varying educational infrastructures and socio-economic conditions.

Finally, the results emphasize the interdisciplinary potential of CT in fostering problem-solving skills across domains, including physics, engineering, and computer science. The interconnected nature of the keyword clusters, as demonstrated in the co-occurrence network, points to opportunities for cross-disciplinary research and collaboration. By addressing existing gaps and leveraging these interdisciplinary connections, educators and policymakers can better integrate CT into curricula, preparing students for challenges in increasingly technology-driven fields.

The study highlights several key gaps in the research on integrating Computational Thinking (CT) into physics education. A significant challenge is the lack of standardized assessment methods to evaluate CT competencies, which limits the ability to measure and compare student outcomes across different studies. Additionally, most research has been conducted in regions with advanced educational infrastructures, such as North America and Europe, while there is a notable scarcity of studies from underrepresented areas, particularly in low-resource settings. The practical implementation of CT into physics curricula also remains underexplored, with limited strategies documented for its integration, especially at the secondary and tertiary education levels. Furthermore, although CT is inherently interdisciplinary, few studies have investigated its application across broader STEM fields or its integration with non-STEM disciplines. Another critical gap lies in teacher training and adoption, as there is insufficient research on how educators can effectively incorporate CT into teaching practices, including professional development and curriculum design. Addressing these gaps is essential to advance the integration of CT in physics education and ensure its effective and equitable implementation globally.

Conclusion

This study underscores the transformative potential of Computational Thinking (CT) in enhancing physics education, particularly in fostering critical thinking, problem-solving, and interdisciplinary skills essential for the 21st century. The bibliometric and systematic review revealed a growing interest in CT integration, with a significant increase in publications after 2015, driven by global initiatives promoting STEM education. The analysis identified three primary areas of focus: CT-based instructional methods, the use of computational tools and simulations for conceptual understanding, and frameworks for assessing CT competencies. These findings highlight the diverse applications and benefits of CT in physics education, ranging from bridging theoretical concepts with practical applications to preparing students for technology-driven challenges.

Despite these advancements, the study identified critical gaps in the research, including the lack of standardized assessment frameworks, limited exploration of diverse educational contexts, and insufficient studies on implementation strategies and teacher training. Addressing these gaps is crucial to fully realize the potential of CT in physics education. Moving forward, researchers, educators, and policymakers should focus on developing inclusive, scalable, and standardized approaches to integrate CT effectively into curricula. By doing so, CT can serve as a cornerstone for preparing students to navigate and succeed in an increasingly complex and technology-driven world.

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