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Theoretical Framework for Integrating Computational Thinking in Quantum Physics Education

Asep Irvan Irvani[1,2], Parlindungan Sinaga[1], Endi Suhendi[3], Lilik Hasanah[3], Rahmadhani Mulvia[2]

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ABSTRACT

This study aims to analyze the theoretical framework of Computational Thinking (CT) integration in quantum physics education, specifically to improve concept understanding, critical thinking dispositions & abilities, and creative problem-solving skills of prospective physics teachers. CT is viewed as a systematic cognitive approach capable of bridging the gap in students' understanding of abstract and mathematical concepts in quantum physics. This study employs a qualitative method using systematic literature review and conceptual analysis of theories, models, and relevant previous research findings, both in the field of physics education and science education in general. The results of the study indicate that CT principles have the potential to improve the quality of students' thinking processes in understanding and solving quantum physics problems logically, reflectively, and creatively. The theoretical framework developed offers the integration of CT into learning design through a problem-based approach and multiple representations, both unplugged and computer-assisted. The conclusion of this study is that CT is not only relevant but also strategic as a foundation for the development of innovative pedagogy in modern physics education. The implications of this study open opportunities for curriculum designers, lecturers, and researchers to adopt and develop CT-based learning strategies in complex courses such as quantum physics, as well as encourage further empirical research to test the effectiveness of the proposed model.

Keywords: *Computational Thinking · Physics Education · Problem-solving · Theoritical Framework · Quantum Physics*

INTRODUCTION

Quantum physics is one of the most intriguing and profound topics in physics education (Bitzenbauer, 2021; Bouchée et al., 2023; Irvani, Rustaman, et al., 2024; Onorato et al., 2024). It provides insights into the behavior of matter and energy at the microscopic scale, which is vastly different from our everyday experiences. Understanding concepts such as superposition, entanglement, and the uncertainty principle is crucial for physics students who wish to understand the subatomic world (Hiller, 2022). Therefore, this course not only serves as a theoretical foundation in modern physics but also lays the groundwork for various advanced technologies, such as quantum computing and quantum communication.

✉ Asep Irvan Irvani
Irvan.irvani@upi.edu

Parlindungan Sinaga
p_sinaga@upi.edu

Endi Suhendi
endis@upi.edu

Lilik Hasanah
lilikhasanah@upi.edu

Rahmadhani Mulvia
rahmadhanimulvia@uniga.ac.id

[1] Science Education Study Program, Universitas Pendidikan Indonesia, Bandung, Indonesia
[2] Physics Education, Universitas Garut, Garut, Indonesia
[3] Physics, Universitas Pendidikan Indonesia, Bandung, Indonesia

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As future physics teachers, students in the physics education program must have a deep understanding of quantum physics concepts (Irvani, Rustaman, et al., 2024; Irvani, Sriyati, et al., 2024). These quantum physics concepts are the foundation of current and future technologies. By mastering these quantum physics concepts, they will be able to educate students who understand and apply the basic principles of physics that underpin many scientific and technological advancements. Mastery of concepts such as Heisenberg's uncertainty principle, wave-particle duality, and quantum field theory will open their minds to the latest innovations in technology, such as quantum computers, quantum communication, and semiconductor technology development.

However, in practice, quantum physics often presents a significant challenge in the learning process (Bouchée et al., 2022, 2023; Michelini & Stefanel, 2023). The abstract concepts and the fact that they are not directly observable in daily life make it difficult for many students to understand this material conceptually. Quantum physics not only requires complex mathematical understanding but also forces students to think outside the box and realize that the subatomic world operates on principles vastly different from the macroscopic world we know. This requires more creative and interactive teaching to help students absorb these complex concepts.

To address this challenge, many quantum physics teachings now adopt simulation and visualization-based approaches to help students understand phenomena that are difficult to grasp through theory alone. Digital technologies, such as physics simulation software, have provided more effective ways to represent abstract quantum phenomena (Hossain, 2023; Krenn et al., 2023; Schröter et al., 2022). It is hoped that through innovations in teaching methods, students' conceptual understanding of quantum physics will improve, paving the way for further scientific discoveries and innovations in the future.

One of the main issues in teaching quantum physics is solving complex problems that require long and intricate mathematical techniques (Batubara et al., 2024; Pospiech et al., 2021). Concepts such as wave functions, operators, and matrix theory often require deep and time-consuming mathematical calculations (Bouchée et al., 2023). Analytical methods used to solve Schrödinger's equation or calculate transition probabilities between quantum states can be extremely difficult, especially for students who are not accustomed to such levels of complexity. This lengthy process can also lead to confusion in linking theory with the results obtained, causing many students to feel hindered in understanding the essence of quantum physics problems.

In this regard, computational thinking (CT) offers a highly promising approach to overcoming these difficulties. CT allows for the systematic and efficient resolution of complex quantum problems (P. J. Denning & Tedre, 2021; Tedre & Denning, 2021). With this approach, students can use algorithms and computational models to break down complex problems into simpler, more understandable steps. For example, through computer simulations or the use of mathematical software, students can quickly obtain numerical solutions to equations that are difficult to solve analytically. This not only saves time but also allows them to gain a better understanding of the phenomena being studied.

The use of computational thinking (CT) in quantum physics also opens up opportunities for students to conduct virtual experiments and simulate various quantum scenarios that are difficult to perform in traditional physics laboratories. In this way, students can more easily explore and visualize highly abstract concepts without being hindered by technical limitations or complex manual calculations (Fokuo et al., 2023; Ziatdinov & Valles Jr, 2022). This approach makes teaching quantum physics more engaging and relevant while also providing practical problem-solving skills that will be invaluable in future academic or industrial careers.

The computational thinking (CT) strategy also holds great potential in enhancing conceptual understanding, critical thinking, and creative problem-solving skills, particularly in the context of complex quantum physics education (Nita et al., 2023; Pipitgool et al., 2021; Voon et al., 2022). Through a systematic approach involving problem decomposition, pattern recognition, abstraction, and algorithms, CT helps students break down and solve complicated problems more efficiently and in a structured manner. This approach not only strengthens conceptual understanding by linking theory to practical applications but also trains students to think critically when evaluating and analyzing information (P. Denning & Wegner, 2012; Weller et al., 2022). Additionally, CT encourages creativity in finding innovative solutions, which is crucial when facing challenges in the field of physics, especially in quantum mechanics, where principles often contradict everyday intuition. Therefore, integrating CT into learning can equip students with the analytical thinking skills required to tackle complex issues in both academic and professional settings.

The aim of this study is to examine the theoretical framework that can be used to integrate computational thinking (CT) into quantum physics education. This is done to establish a deep theoretical foundation on how computational thinking can be effectively applied in the context of quantum physics education, as well as to explore ways in which this integration can help students overcome challenges in understanding and solving complex problems in quantum physics. By developing and examining this theoretical framework, it is hoped that more efficient and applicable learning strategies will be created for prospective physics teachers to teach quantum material in a more comprehensive and relevant manner.

METHOD

This study uses a qualitative approach with a systematic literature review method and conceptual analysis to build a theoretical framework for integrating computational thinking (CT) into quantum physics education. This approach was chosen due to the research focus on examining theoretical concepts related to teaching quantum physics and the role of CT in enhancing students' understanding and critical thinking skills (Luft et al., 2022; Makri & Neely, 2021; Salawu et al., 2023). Through the literature review, this study aims to establish a deep theoretical foundation and provide new insights into the use of CT in physics education.

The research instrument involves the analysis of theories and models relevant to computational thinking (CT) and quantum physics education. The researcher explores various problem-based learning approaches and the use of multiple representations in integrating CT into quantum physics education. This approach is expected to provide a clearer picture of how CT can be adapted to enhance the understanding of complex concepts in quantum physics and assist students in overcoming difficulties that arise during the learning process.

Data collection techniques were carried out through a literature review from various relevant sources, including previous research in the field of physics education and the application of computational thinking (CT) in science education. The data collected includes literature discussing the challenges in quantum physics education, as well as studies that examine the role and effectiveness of CT in supporting science education in general. Data analysis was conducted by organizing and testing existing theories to understand the impact of using CT in quantum physics education. With this approach, the study aims to produce a strong theoretical framework for the integration of CT into quantum physics education that is more effective and applicable.

RESULT AND DISCUSSION

In this section, there will be three main areas of discussion. First, the discussion will focus on the relationship between computational thinking (CT) and deep conceptual understanding, critical thinking, and creative problem-solving. The second focus will be on the potential strategies of CT that can be applied in quantum physics education. The final discussion will center on the conceptual framework that supports the CT strategy in quantum physics education.

The Relationship Between Computational Thinking and Deep Conceptual Understanding, Critical Thinking, and Creative Problem-Solving

The relationship between computational thinking (CT) and conceptual understanding, critical thinking, and creative problem-solving is crucial in quantum physics education. CT helps students break down complex problems into smaller, more structured parts, making it easier to understand quantum physics concepts that are often abstract and difficult to grasp (Bouchée et al., 2023; P. J. Denning & Tedre, 2021). With a CT-based approach, students can identify patterns, create representations, and develop algorithms to solve complex quantum problems, which in turn deepens their understanding of these concepts.

The use of computational thinking (CT) in quantum physics education can enhance students' critical thinking skills. CT encourages students to think analytically and systematically when solving problems, which is an essential aspect of critical thinking (Chen et al., 2023; Lai & Wong, 2022; Voon et al., 2022). By using decomposition and pattern recognition methods in the context of quantum physics, students are trained to identify and evaluate information more sharply. This hones their ability to critique arguments and make decisions based on available evidence, which is an integral part of critical thinking.

The application of computational thinking (CT) also supports the development of creative problem-solving skills (CPS), which involve the ability to find innovative solutions when facing complex challenges. In the context of quantum physics, problems often do not have a single, clear solution and require a creative approach to resolve them. By integrating CT, students can explore various potential solutions through virtual experiments and computer simulations, which opens opportunities for them to find more efficient and creative solutions (Agbo et al., 2023; Chevalier et al., 2020; Dwyer et al., 2014; Simanjuntak et al., 2021; W. Zhang et al., 2024). These skills also give students the freedom to think beyond conventional boundaries, creating more innovative approaches to solving quantum problems.

In summary, the relationship between computational thinking (CT) and deep conceptual understanding, critical thinking, and creative problem-solving is shown in Table 1 below.

Table 1. The Relationship Between Computational Thinking and Deep Conceptual Understanding, Critical Thinking, and Creative Problem-Solving

No.	Element	Relationship with Computational Thinking (CT)
1	Deep Understanding	CT enhances deep understanding of computational concepts such as algorithms, abstraction, and data analysis (Kaup et al., 2023; Ye et al., 2023). It enables individuals to apply computational principles effectively in solving complex problems, which deepens their conceptual understanding of physics, particularly in quantum mechanics.
2	Critical Thinking Dispositions (CTD)	CT encourages the development of critical dispositions, such as perseverance in finding solutions, openness to various approaches, and creativity in designing computational solutions(Hamidi, 2025; Voon et al., 2022). Integrating CTD with CT helps individuals approach problems with an analytical, critical, and innovative mindset, fostering a more open-minded attitude towards learning and problem-solving.
3	Critical Thinking Abilities (CTA)	CT strengthens critical thinking abilities by requiring in-depth analysis, careful evaluation, and systematic problem-solving within a computational context (Pipitgool et al., 2021; Voon et al., 2022). By applying CT, individuals can directly hone their CTA skills, developing logical reasoning and the ability to evaluate and solve problems efficiently in complex scenarios.
4	Creative Problem-solving Skills (CPS)	CT promotes creative thinking in designing effective solutions within a computational framework (Arslantaş, 2025; Piatti et al., 2022). Integrating CT with CPS allows individuals to develop innovative and efficient solutions, using their creativity to explore new approaches and effectively address complex challenges in quantum physics and other scientific fields.

Computational Thinking Strategies in Quantum Physics Education

The Computational Thinking (CT)-based quantum physics learning strategy is an educational approach designed to achieve course objectives through the integration of key CT concepts, namely decomposition, pattern recognition, abstraction, and algorithms (Li et al., 2020; Wing, 2006, 2014). This strategy aims to help students analyze, design solutions, and solve complex problems found in quantum physics.

This learning strategy is comprehensively designed to enhance students' logical, mathematical, and algorithmic reasoning abilities (Polat et al., 2021; Rahmawati et al., 2024; Wang et al., 2022). This approach utilizes core concepts of Computational Thinking (CT), applied specifically to address complex problems in quantum physics. An explanation of the CT strategy in quantum physics education is presented in Table 2.

Table 2. Explanation of Computational Thinking (CT) Strategies in Quantum Physics Education

No.	Element	Description	Implementation Example
1	Decomposition	Breaking down complex problems into smaller parts to make them easier to understand and solve.	When studying the Schrödinger Equation, students separate aspects such as potential energy, wave functions, and boundary conditions.
2	Pattern Recognition	Identifying similarities or patterns in problems to accelerate the analysis and solution process.	Students recognize solution patterns in an infinite potential well that are similar to those in the quantum harmonic oscillator approach.
3	Abstraction	Focusing on relevant information and filtering out	In analyzing particle interactions, students focus on the total energy of the system

No.	Element	Description	Implementation Example
		insignificant details for problem-solving.	without being distracted by complex mathematical details.
4	Algorithm	Designing systematic steps or logical procedures to solve problems.	Students create simple algorithms to calculate the expected value of the wave function in a given potential.

Conceptual Framework

The thinking theories and educational theories that support Computational Thinking (CT) involve key concepts that strengthen the importance of developing computational skills in modern education. Some of the theories supporting CT include Computational Thinking Theory, Constructivism Theory, Cognitive Learning Theory, Problem-Based Learning Theory, and Social Constructivism Theory.

The conceptual framework of Computational Thinking (CT) serves as the foundation for designing quantum physics courses in accordance with the theories that support it. The relationships between these theories are depicted in the conceptual framework diagram in Figure 1 below.

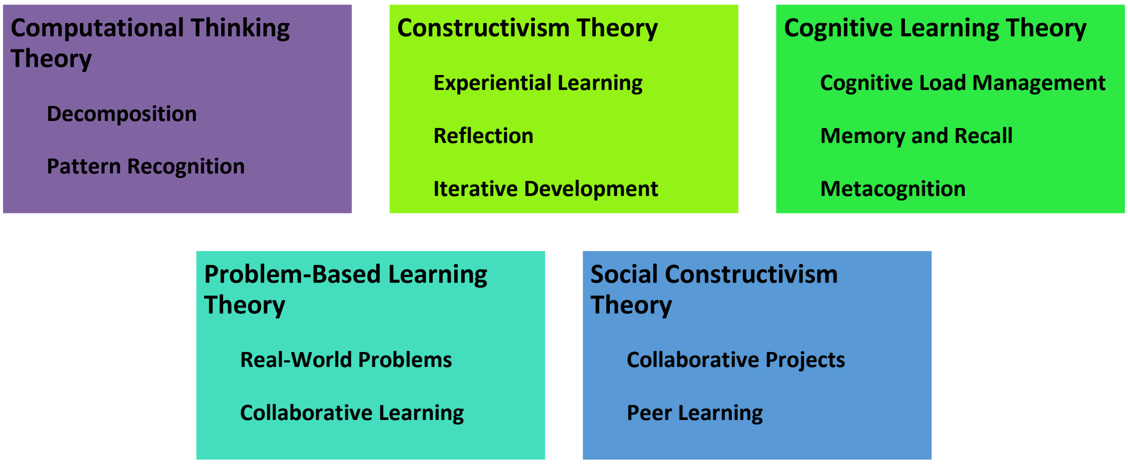

Figure 1. Visualization of the Computational Thinking Conceptual Framework

Computational Thinking Theory focuses on four fundamental concepts: Decomposition, Pattern Recognition, Abstraction, and Algorithm Design (Silva et al., 2020; Wing, 2006). In quantum physics, these techniques allow students to break down complex problems into manageable parts, identify patterns, and design algorithms for solving difficult problems, such as Schrödinger's equation or wave modeling.

Constructivism Theory supports experiential learning, reflection, and iterative development (Bindal, 2022; Passarelli & Kolb, 2023; M. J. Zhang et al., 2022). Students actively build their knowledge by solving relevant challenges, and through reflection on the learning process, they gain a deeper understanding of how quantum physics applies in the real world.

Cognitive Learning Theory emphasizes managing cognitive load, as well as memory and recall (Castro-Alonso et al., 2021; Curum & Khedo, 2021; Skulmowski & Xu, 2022). This theory aids students in processing and retaining complex quantum concepts, making them more accessible and easier to understand.

Problem-Based Learning Theory emphasizes solving real-world problems (Maftuh et al., 2023; Tanna et al., 2022). It encourages collaboration and self-directed learning, which are essential for tackling the abstract and challenging nature of quantum physics.

Social Constructivism Theory promotes collaborative projects and peer learning (Rannikmäe et al., 2020; Saleem et al., 2021). It encourages the development of practice communities where students can support each other in enhancing critical thinking skills, particularly in solving complex quantum problems.

By integrating these theories into quantum physics education, students can gain a deeper understanding and stronger problem-solving skills, which are essential in the challenging and abstract context of quantum physics education. This enhances the potential of computational thinking in improving both the output and outcomes of quantum physics learning.

CONCLUSION

Based on the findings of this study, it can be concluded that the integration of Computational Thinking (CT) in quantum physics education has great potential to enhance students' conceptual understanding, develop critical thinking skills, and facilitate creative problem-solving. With a systematic approach involving problem decomposition, pattern recognition, abstraction, and algorithm design, CT can help students solve complex quantum problems more efficiently and in a structured manner. The application of CT equips students with essential skills to identify and solve challenges in quantum physics, which are often abstract and require deep mathematical understanding.

The findings of this study indicate that Computational Thinking (CT) is not only relevant but also strategic for the development of innovative pedagogy in modern physics education. By integrating CT into the learning design, such as through problem-based approaches and multiple representations, quantum physics education can become more engaging and effective. This research also opens opportunities for curriculum developers, lecturers, and researchers to adopt and develop CT-based learning strategies, which in turn will enhance the effectiveness of quantum physics education in the future.

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