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State of The Art Review: Building Computational Thinking on Science Education

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Abstract

Industrial Revolution 4.0 requires individuals to have the ability in the field of technology and use it to solve existing problems. Computational Thinking (CT) is one of the skills needed in dealing with technological developments through a problem-solving process. Many research developments in the field of CT have been carried out, but the theoretical studies presented are still limited to the ability in solving problems using a computer. Whereas in its development, CT theory must be adapted to the scope and purpose of building it. Based on that, new research is needed which aims to test and analyze the truth of these findings and examine the stages of building appropriate CT for science students with state-of-the-art review method. By taking a specific scope that has not been studied by many researchers, namely science education, it is found that CT is the ability in dividing a problem into sub-steps, carry out deeper investigations, analyze and criticize and test the truth of something so that the right solution is obtained. This definition is more specific than the definition of CT in theory because it is adapted to the characteristics of science. Whereas from a state-of-the-art review of the stages of building CT, it was found that the stages of task decomposition, abstraction, generalization, data structures and algorithms were considered to optimalize the CT construction for science students. It is because students could identify tasks or problems and divide the problem into small parts at the task decomposition stage. Therefore, they can be completed one by one.

Key words: computation thinking; science education; state of the art review

INTRODUCTION

Technological advances in the era Industrial 4.0 have led to automation in all fields. Technological advancements are capable of connecting the physical world and the digital world, thereby influencing human lifestyle and interactions. Information exchange is very rapid and dynamic. The industrial revolution will fundamentally transform industries and the nature of work, even giving rise to new types of jobs. Many jobs will disappear due to automation (Siswati, 2019). This undoubtedly presents a challenge for individuals to be prepared for changes that occur in accordance with technological advancements, so that they remain competitive and not left behind.

A technology-rich society requires three different skills for individuals to keep up with its development. First is the ability in using basic computer applications. This skill is generally defined as computer literacy. Second is the ability in understanding how computer systems work. This is generally defined as computer fluency. Third is the ability in using computer techniques or applications to solve specific problems. This skill is currently known as computational thinking (CT).

The ability and skills of individuals in facing the era of technological development must be prepared from now on. These skills are in line with the demands of the 21st century, which are the ability in solving problems and think critically (Problem Solving and Critical Thinking), communicate (communication), collaborate (collaboration), and think creatively (creative thinking). Other skills needed are CT. Li et al. (2020) stated that CT is widely recognized as something important for individuals to have in the 21st century.

Education plays an important role in building the necessary abilities and skills to face technological advancements, as education itself is also affected by these developments. Technology gives the rising of digital competencies and programming and becomes part of the curriculum (Kjällander Mannila, Åkerfeldt, & Heintz, 2021; Dinata, 2021). All activities in the world of education have shifted towards digitalization, such as digital libraries, online learning, and e-books. Therefore, the habit of using technology can be started from education, and building this ability can also be done through integration into the learning process in the classroom (Tanjung, Wulandari, Bakar, & Ramadhani, 2021).

Individuals' ability in using technological tools is expected to keep up with the rapid pace of technology advancement. Many requirements are needed to enter a job related to computers, so that making building CT and digital literacy essential for individuals. CT mastery is an effort to prepare entering the world of work that is based on complex computing technologies such as artificial intelligence, robotics, and the Internet of things (Kale et al., 2018). In reality, educational institutions have not yet caught up with the needs of the future workforce (Ansori, 2020).

Integrating CT in learning is expected to prepare learners with the skills that are in line with the needs of the workforce. The shift towards digitalization in every aspect makes CT skills essential in the workplace. All fields of expertise and jobs require computerization and digital skills, and it is predicted that starting in 2020, robots or automated machines will be more needed than humans. Therefore, mature preparation and implementation are needed in integrating CT into learning that follows the times.

Integrating CT in schools is one of the efforts to build computer literacy and 21st-century skills. The integration of technology in education is crucial for aligning with the challenges of the industrial era and developing 21st-century life skills (Palts & Pedaste, 2020). CT skills are related to 21st-century skills (Critical Thinking, Communication, Collaboration, Creativity) because several studies state that CT can be developed through critical thinking and problem-solving processes, resulting in creative solutions (Taslibeyas, Kursun, & Karaman 2020; Romero, Lepage, & Lille, 2017; Noh, 2020; Zakaria & Iksan, 2020; Ansori, 2020).

Problem-solving, critical thinking, and creativity competencies are part of 21st-century skills that align with CT. CT is one of the 21st-century skills applicable to problem-solving processes and daily activities (Romero et al., 2017; Noh & Lee, 2020; Lee et al., 2020; Zakaria & Iksan, 2020; Ansori, 2020). The importance of CT skills in the 21st century has opened the eyes and minds of educators to develop and cultivate these skills through the teaching and learning process in the classroom.

One of the current educational efforts in Indonesia to develop 21st-century skills is the implementation of the Curriculum Merdeka, which is more flexible and focuses on essential subjects as well as the character and competence development of students. In the implementation of the Curriculum Merdeka, the use of technology plays an important role, making CT one of the target skills to be achieved by students

CT describes specific skills related to computer science and other disciplines (Taslibeyas, Kursun, & Karaman, 2020). Several studies outline that CT is a problem-solving skill that utilizes computers. However, based on the basic theory, preliminary studies, and the development of research, CT does not necessarily require mastery of computer programming. Instead, it emphasizes structured thinking in problem-solving efforts (Agbo, Oyelere, Suhonen, & Laine, 2021; Buitrago et al., 2017). Many new definitions have emerged from the concept of CT, necessitating further in-depth research using state-of-the-art review techniques to discover new knowledge within the educational scope.

CT is not limited to computer proficiency, but extends beyond that as a new concept in problem-solving efforts. CT is no longer considered a difficult skill to develop in 21st-century students, as there are various learning models and stages for building CT that educators can utilize. Based on this, a state-of-the-art review technique is employed to identify appropriate learning models and stages for building CT within the educational context, especially in science education.

In science education, CT is generally defined (similarly to other educational studies) and limited to computer usage, whereas according to the nature of science, which consists of three elements: science as a process, science as an attitude, and science as a product, CT should play a significant role in building scientific process skills, where inquiry is an integral part of these skills.

Based on the review highlighting the importance of students possessing CT skills, particularly in science education, the objectives of this research are to map CT publications in science education to identify opportunities for new studies on CT topics for future research development. Additionally, it aims to analyze and examine the concept of CT and the stages of building CT in science education through a state-of-the-art review, leading to the discovery of novelty from a specific perspective. The state-of-the-art summarized in this article is expected to contribute to the establishment of CT theory.

METHOD

The method used in reviewing this article is a State of the Art (SOTA) review with stages adapted from Kitchenham & Charters (2007), namely planning, conducting, and reporting (Figure 1). These three stages are general stages in a series of activities to obtain the appropriate research subject. The research subject consists of articles published between 2017 and 2022 that discuss CT and the stages of building CT in science education.

The data collection technique used is observation and direct review of a selected number of articles that meet the criteria. The stages of this research are as follows: the planning stage is carried out by identifying the review's needs and determining the problem formulation to be reviewed based on literature sources. The problem formulation for this study is how the concepts and stages of building CT in science education are based on a state of the art review. The conducting stage involves searching for journal article data using the Mendeley reference manager application, with search keywords using the phrase "Computational Thinking on Science Education." The reporting stage involves conducting a deeper analysis and drawing conclusions and evaluations from the entire literature review.

In the literature search activity, 1447 articles related to this keyword were found. After checking the suitability of the articles based on the publication year (at least 2017), the number of articles obtained was reduced to 1141. From these articles, a selection was made according to specific criteria, resulting in a final set of 78 articles. The criteria used by the researchers include articles published in reputable international journals indexed by Scopus and Web of Science (WoS), or reputable national journals indexed by SINTA, articles published between 2017 and 2022, and articles that contain CT theory and the stages of building CT.

Out of the 78 articles, further filtering was done based on the variables to be studied, resulting in the selection of 13 articles that specifically examine CT and the stages of building CT in science education. These 13 articles were reviewed using a state of the art review, comparing theories and stages of building CT to identify suitable theories and stages for application in science education. The compilation of state of the art statements and descriptions can use the conjunction "however".

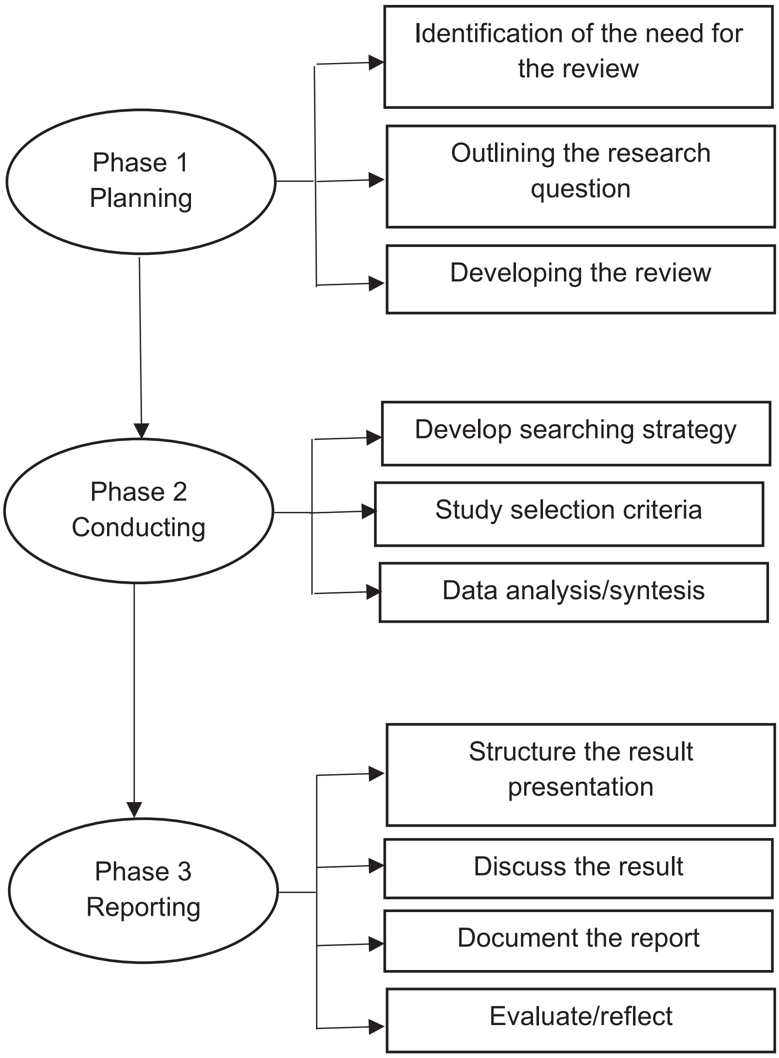

Figure 1. The Stages of Article Review (Adoption from Kitchenham & Charters , 2007)

RESULTS AND DISCUSSION

This study utilizes deductive techniques, starting from mapping and discovering general aspects before moving on to specific aspects. Based on the filtering results according to the criteria set by the author, a total of 78 articles from 2018-2022 were selected, which were further filtered to obtain 13 articles related to education. These articles are reviewed to gain new knowledge related to CT in science learning.

Based on the analysis of mapping 78 articles, a data summary was obtained in the Table 1.

Table 1. The Initial Data Summary of CT Article

Data Components	Results
Total Documents	78 articles
Year of publication	2017 (3, 3.9%), 2018 (7, 8.9%), 2019 (12, 15.3%), 2020 (25, 32%), 2021 (25, 32%)
Types of research	Literature Review/Meta Analysis/Descriptive (31, 39.7%) Development/Design (12, 15.4%) Experiment/Survey/Correlation/Exploration (30, 38.4%) Mix Methods (5, 6.4%)

Keywords/Variables associated with CT	*Programming, Problem Solving, STEM, Assessment, Computer Science, Higher Education, Abstraction, Creativity, Mathematics, Science Education, Education, Educational Technology, Decomposition, Digital Competence, Engineering, Primary School, Scratch, algorithm, Evaluation, teacher education , strategies , Learning analytics, educational robotics , secondary education , Validity, Reliability, Technology, Pre-service Teacher, Self-Efficacy*

From the 78 articles, it is known that CT has been studied with other variables through four types of research. The variable that has been studied the most is CT associated with programming, problem solving, STEM, and science education. The data on the occurrence of these keywords or variables can be seen in the visualization of CT publications using VOSviewer in Figure 2.

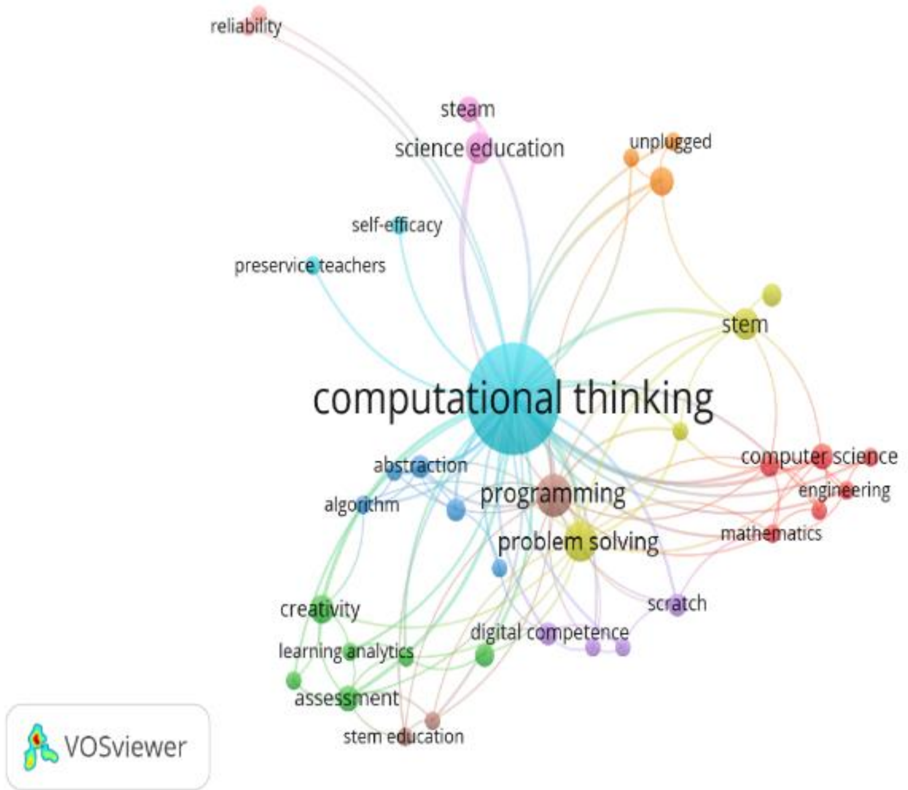

Figure 2. The Visualization of CT Publications Based on Keywords

Publications on CT are more dominant, and other keywords related to CT are represented by denser circles such as programming, problem solving, STEM, assessment, computer science, higher education, creativity, and others. Keywords with fewer occurrences include CT associated with pre-service teachers and self-efficacy. This indicates opportunities for new studies with CT topics related to these two keywords, which can be beneficial for the development of future CT research.

State of the Art CT Study

Based on previous theories and research, CT involves techniques for problem-solving, system design, and understanding human behavior by describing the fundamental concepts of computer knowledge. The essence of CT is to think like a computer scientist when faced with a problem (Wing, 2006).

The history of CT began before Wing's research, with Alan Perils (1962) from the Association for Computing Machinery advocating for integrated computer programming learning Subsequently, Donald Knuth (1974) presented a decade of CT theory, emphasizing the need for understanding tasks through computer performance. Seymour Papert then promoted the goal of teaching students to think through programming (Papert, 1980). However, out of all these concepts, Wing's CT concept is explicitly recognized as a reference for the study of CT in the 21st century (Grover & Pea, 2013; Shute, Sun,& Asbell, 2017). The works of Perils, Knuth, and Papert embody the spirit of CT and build the concept of the relationship between computer science and human cognition (Bull, Garofalo, & Hguyen, 2020).

Wing's theory (2006) served as the starting point for critical studies of CT in K-12 education, and in a review of her theory in 2011, Wing redefined CT as a process of formulating problems and finding solutions, which are subsequently presented in some form by individuals (Wing, 2011). Aho (2021) simplifies the definition of CT as a process of formulating problems and presenting solutions as computational steps and algorithms. CT has since become a current research issue and has attracted the interest of researchers, educators, and policymakers, leading to significant advances in learning ((Hsu, Chang & Hung,2018).

Wing's CT theory provides the foundational theory but is limited in its narrow scope, while the field continues to evolve, resulting in a shift in the meaning of CT. Many recent studies examine CT due to the need to align education with the digital and social revolution that directly changes the way we learn, work, and face life (Ezeamuzie & Leung, 2022). By harnessing CT skills, learners can find solutions to complex problems while training systematic thinking processes (Buitrago et al., 2017).

The current development of CT research presents the opportunity for negative impacts on the core concept of CT. The current definition of CT has become unsettled, causing confusion for researchers who want to conduct similar studies. Grover & Pea (2013) express similar concerns about various definitions of CT. They call for further studies to compare theories, standardize, and generalize CT theories when faced with various instructional/learning strategies (Buitrago et al., 2017; Hsu et al., 2018; Lye & Koh, 2014), diverse assessment methods (Cutumisu, Adams, & Chang, 2019; Shute et al., 2017; Tang et al., 2020), and changing multimedia used by educators in learning (Xia & Zhong, 2018; Yu & Roque, 2019; Zhang & Nouri, 2019). This undoubtedly presents a challenge to accurately establish the definition of CT, particularly in educational environments such as professional teacher development (Menekse, 2015), higher education (Czerkawski & Lyman, 2015), and early childhood education (Bers, 2017).

The current development of CT theory from recent studies provides different descriptions from Wing's theory and other pioneers, but there are several developments in the definition. To explicitly define CT as a logical thinking possessed by humans in an experimental investigation (Allsop, 2019; Kim et al., 2013, Rodriguez, 2021). Specifically, Yadav et al. (2018) define CT according to Wing's CT concept (2006) as a way of thinking or a thinking habit similar to that of a scientist. CT is a way of thinking and practicing computation, as well as a way to positively solve problems. However, it is not mandatory to use technology to solve problems but rather to guide learners to solve problems with technological concepts (Lin & Chen, 2020). CT is a fundamental skill for everyone, not just computer scientists. CT is comprehensive thinking that encompasses mathematical thinking, engineering thinking, and scientific thinking (Korkmaz & Bai, 2019). CT as a problem-solving process promotes skills such as problem formulation, solving complex problems to find main ideas, and finding solutions using computers (Kukul & Karatas, 2019; Özgür, 2020; Taslibeyaz et al., 2020). The ability in generating ideas requires individual creativity (Tanjung & Nasution, 2022), so CT is also related to problem-solving skills and creative thinking.

Based on these definitions, it can be seen that the study of CT is related to how individuals' thinking processes manage problems and seek solutions with certain patterns, which simultaneously require rational, critical, and creative thinking skills as well as appropriate decision-making. It does not necessarily require the use of computers, but rather thinking in a CT manner with specific algorithms. CT is an approach that does not always involve computer programming but rather an approach to problem-solving that uses strategies such as algorithms and abstraction.

The Innovation of CT Concepts in Science Education

Specifically for the study of CT associated with science education, researchers mapped and examined 13 articles obtained from filtering 78 articles published between 2018 and 2022 that specifically investigated CT in science education, to facilitate the delineation of the state of the art of CT concepts in science education.

Based on the study of these 13 articles, CT in science education is not limited to problem-solving. CT is seen as an important skill in addressing problems that arise in a society driven by complex science and technology. It involves the ability in thinking computationally, design and evaluate complex systems, and understand individual reasoning and behavior. CT is closely linked to technology, as technology is considered a means to achieve CT in science.

In science education, CT serves as a stimulus for curiosity, experimentation, collaboration, social interaction, problem-solving, and learning. Based on this, CT is implemented and can be developed through STEM (Science, Technology, Engineering, and Mathematics) learning practices (Burbaite, Drasute & Stuikys, 2018; Ching, Hsu & Baldwin, 2018; Città et al., 2019; En, 2021; Gilchrist et al., 2021; Lee & Malyn-Smith, 2020; Li, 2020; Palts & Pedaste, 2020). STEM is capable of reflecting creativity, algorithmic thinking, critical thinking, problem-solving, and collaboration skills. STEM-based learning can shape learners' abilities to think critically, logically, and systematically (Ramli & Yohandri, 2020). In the STEM approach, CT is a set of cognitive skills that guide learners in investigating patterns, solving problems, controlling and determining solutions, and building data representations through simulations (Tekdal, 2021). CT is optimized when it is associated with the STEM approach, leading to a more comprehensive achievement of scientific understanding (Burbaite et al., 2018; En et al., 2021).

The combination of the four aspects of STEM with the stages of CT becomes a complex learning activity. Implementing learning through computational media and CT skills can maximize STEM-oriented education. There is a symbolic relationship between STEM and CT (Fantuzzo et al., 2011; Repenning et al., 2010). The integration of CT with STEM content can guide learners to explore, apply, and develop ideas, as well as their abilities within the context of STEM. Therefore, STEM is well-suited for the development of student's computational thinking. In this regard, STEM is closely related to technology (Ramadhani et al., 2022). Educators play a significant role in managing the classroom to integrate the stages of CT and facilitate students in acquiring these abilities.

Another finding is that CT can be developed not only through STEM education but also through other instructional models such as inquiry-based learning and problem-based learning. The implementation of the inquiry-based model has a positive impact on problem-solving skills (Turnip et al., 2016). Inquiry-based learning based on CT has been examined by Dolgopolovas et al. (2019). Based on this research, it is concluded that science, which is synonymous with inquiry-based learning, can be integrated with the stages of CT, allowing science-related problems to be solved in a more systematic and accurate manner

In the concept of science, students with CT skills are not solely focused on problem-solving; instead, they attempt to analyze it, gather data about it, and break it down into sub-steps (Kiyici & Yamak, 2021). All these stages are carried out with reasoning and scrutiny of their validity. This is a characteristic of CT in science education, where computational abilities are used to maximize the analytical and investigative aspects of problem-solving. A learner who possesses

CT in science education doesn't just utilize it for problem-solving but also to aid in conducting deeper investigations, analyzing, and testing the validity of phenomena to arrive at accurate solutions. In this context, CT becomes a form of scientific literacy employed to discover solutions (Park & Green, 2019).

The development and internalization of CT skills in a computer-free environment can be supported by science education, through appropriate learning processes that cater to learners' foundational abilities, provide varied learning experiences, employ inquiry and computational-supportive teaching models, and adopt interdisciplinary approaches to teach scientific concepts.

Stages of Building CT in Science Education

Several studies have outlined the stages of building CT so that learners can develop this skill, similar to other thinking skills such as creative and critical thinking. In fact, CT can enhance these thinking skills to a greater extent. Research studies have indicated that CT can be developed through critical thinking and problem-solving processes, leading to creative solutions (Taslibeyaz et al., 2020; Romero et al., 2017; Noh, 2020; Zakaria & Iksan, 2020; Ansori, 2020). The stages involved in building CT include data practices, modeling and simulation practices, computational problem-solving practices, and systems thinking practices (Arastoopour et al., 2020; Bati, Yetişir, Çalişkan, Güneş, & Saçan 2018; Gilchrist et al., 2021). Data practices involve understanding and mapping data to determine appropriate solutions. Modeling and simulation practices are related to searching for models or formulas to solve problems once the problem is identified. Computational problem-solving practices involve processing problem-solving using algorithmic thinking. Systems thinking practices involve creating systematic connections between the different stages of building CT to generate appropriate solutions.

The discovery and innovation in these stages of building CT lie in the implementation of these stages to maximize CT in science education. Stages that have not been specifically researched by scholars are task decomposition, abstraction and generalization, data structures, and algorithms (Burbaite et al., 2018; En et al., 2021). These stages are similar to abstracting problems, automating problems, abstraction, decomposition, generalization, algorithmic thinking, and evaluation (Park & Green, 2019; Silva et al., 2020).

Decomposition is breaking down a problem into smaller and simpler parts to be solved one by one and identified individually. Abstraction and generalization involve identifying and generalizing concepts from the problem to create problem-solving patterns. Data structures and algorithms are the processes of solving problems using step-by-step procedures that can be used by others and yield the same solution. These steps represent an algorithmic thinking process. The final stage is evaluation. Evaluation is the stage to examine the process and results of problem-solving to determine if they are appropriate and acceptable as solutions.

Based on the development of the stages in CT building and considering the characteristics of science education, the stages based on task decomposition, abstraction and generalization, data structures and algorithms are considered to focus in the construction of CT of science education students. In the task decomposition stage, students can recognize tasks or problems and break them down into smaller parts to be solved one by one. This can potentially become a new research topic for researchers as it contains elements of novelty in the application of these stages in science education. The technical implementation details will undoubtedly generate researchers' interest, leading to the further development of CT theory and its application in science education in general, and specifically in Physics.

CONCLUSION

CT in science education is the computational ability used to maximize the investigative and analytical skills in problem-solving processes. Students who possess CT in science learning not only use it to solve problems but also to help break them down into sub-steps, conduct in-depth investigations, analyze and critique, and test the validity of information in order to arrive at accurate solutions. CT can be developed in science education in general and specifically in Physics through the practice of inquiry-based learning models and problem-based learning models based on STEM by combining stages of CT development such as task decomposition, abstraction and generalization, data structures, algorithms, and evaluation

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