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Students' Computational Thinking Skills in Physics Learning: A Case Study of Kinematic Concepts

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ABSTRACT

Physics learning provides a context for future careers in fostering ability in high-end logic with the 21st learning goals. Applying computational thinking in schools is challenging and requires systemic transformation and teacher attention. This study aims to investigate the computational thinking of students in physics learning. This study used exploratory qualitative research. Data were gathered through observation, interviews, and portfolio documents. The data are analyzed through six stages: preparing and organizing, exploring, building descriptions, representing the findings, interpreting the results, and validating the accuracy. The result indicated four primary computational thinking skills: decomposition, abstraction, simulation, and evaluation. The computational thinking skills in physics learning can develop students' understanding and implementation of physics concepts based on data, not just mathematical formulas. Computational thinking in physics learning gives students the opportunity and space to explore and develop their ideas and logical reasoning more deeply in problem-defining, solutions, and evaluation. Students use their logical reasoning to solve the problem precisely. This study is expected to be used as a basis and support for physics teachers to integrate computational thinking into their learning classroom.

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I. Introduction

Computational thinking is widely studied in the 21st century as a new paradigm of thinking and developing science and technology. The 21st century has transformed various skills, knowledge, and competencies required in modern society [1]. Research related to integrating computational thinking in learning is an exciting issue [2]. Integrating computational thinking into the classroom is challenging and requires systemic transformation, teacher attention, and learning resources [3]. Computational thinking is an essential thinking skill crucial in helping individuals solve problems [4]. Computational thinking refers to systematically analyzing, investigating, and testing solutions to complex problems [5]. Computational thinking is a cognitive process that involves a complex logical sense [6], [7]. Providing the young generation with complex and challenging problem-solving skills will be significantly valuable in dealing with developments in an increasingly complex and dynamic future era [8].

Applying computational thinking in schools is exciting and challenging. Computational thinking is an essential skill that must be integrated and marked from early education to solve the problem effectively [9]. Giving a complex problem increases the young learner's capabilities to solve a dynamic situation [8]. Computational thinking involves multiple-level abstraction processes used across multidisciplinary subjects and applied in the virtual and the complex real world [10]. Also, it combines much cross-disciplinary knowledge such as science, technology, engineering, mathematics, social, and literacy [7], [11], [12]. Computational thinking contains many high-level skills, such as creativity, critical thinking, algorithmic thinking, collaboration, and problem-solving [13]. Students are expected to solve problems and be responsible, transform what is learned, analyze, interpret scientific data, and use technology appropriately [14]. Skills related to creativity, curiosity, critical thinking, literacy, and technology are required for students' existence in their future careers [15]. Therefore, teachers must prepare students as the younger generation with computational thinking skills.

Physics education is crucial to encourage the workforce to compete in the industrial revolution 4.0. Physics education supports technological development and prepares students to make advanced scientific progress and discoveries [16], [17]. Physics provides a context for future careers promoting profound knowledge and boosting proficiency in high-end logic parallel with the twenty-first-century learning goals [16]. Physics is a prerequisite for engineering and technology and is appropriate for all sciences. Advancements in technology are commonly established on discoveries in physics and inventions based on new construction of current physics knowledge [18]. Learning physics equips the required skills for scientific thinking, constructing knowledge, keeping track of developing technology, analyzing, and interpreting phenomena in nature [19]. Physics learning helps students analyze complex problems and understand natural phenomena [17].

Unfortunately, several students think physics learning is accustomed to conventional education by directly using mathematical formulas [20]. Students are frightened to study physics because it has a standing as a complex and complicated subject [21]. Particular considerations of physics that they uncover enormously include the need to realize various mathematical equations and figures and then be able to convert those concepts into actual life [22]. In addition, computational thinking research in physics learning is infrequently accomplished [21], [23]. This study aims to investigate students' computational thinking skills in physics learning. The research question of this study is what are students' computational thinking skills in physics learning?

II. Theory

Computational Thinking Skills

Several researchers have proposed definitions of computational thinking. Each researcher has a different interpretation. The variety of descriptions illustrates that computational thinking and its facets are not limited to computer-related practices but have a broader meaning [24]. Xu and Tu [25] also clarified that computational thinking skills universally involve various mental and thinking processes that reflect computer science and meaningful frameworks. Computational thinking is a way of thinking, investigation, and action, which can be established using specific skills to assess performance-based computational thinking [26], [27]. It is a process of formulating problems and solutions that can be represented more effectively and efficiently [28]. Alfayez and Lambert [29] stated that computational thinking involves intellectual skill, practice, and methods to solve a complex problem. In other representations, the scope of computational thinking is broader and a complex process that can be described through the knowledge, attitudes, and general practices that supplement it [30]. Table 1 represents some characteristics/facets of computational thinking.

Table 1. Characteristics of computational thinking

Authors	Characteristics of computational thinking skills
Wing [31]	Abstraction, decomposition, problem reformulating
Barr & Stephenson [32]	Abstraction, algorithm and procedure, decomposition, automation
Brennan & Resnick [33]	Computational concept, computational practice, computational perspective
Aho [34]	Algorithm design and problem-solving technique
Grover & Pea [35]	Abstraction, algorithm notation, automation, structured and logical problem solving, decomposition, iterative thinking, recursive and efficient
Weintrop et al. [36]	Practical data, modeling, and simulation practicum, computational problem-solving practice, systems thinking practice
Shute et al. [26]	Decomposition, abstraction, algorithm design, debugging, iteration, and generalization
Kale et al. [37]	Confrontation, decomposition, pattern recognition, abstraction, algorithm, automation, analysis
Lee & Malyn-Smith [10]	Abstraction, algorithm, developing a program, data collection & analysis, modeling & simulation
Ehsan et al. [38]	Abstraction, Algorithms and procedures, troubleshooting and debugging, pattern recognition, simulation

Computational Thinking Skill in Education

Instruction and learning are becoming challenging due to technical and technological information development in the 21st century. Exploring computational thinking in education is a fundamental skill that facilitates students to explore their ability to solve problems [10], [39]. Integrating computational thinking requires many skills, from teaching strategies to utilizing computer knowledge to teach subject matter [37]. Schools and teachers should collaboratively support the teaching of computational thinking skills to their students [40]. The academic perspective views that computational thinking skills will improve math and science content knowledge [7], [12], [41]. Wing [42] stated that reading, writing, and arithmetic must add computational thinking skills to children. Bringing computational thinking and practice to classroom learning will provide students with a more realistic and contextual interpretation [7], [43], [44]. Computational thinking can effectively teach a more challenging and meaningful body of knowledge [12]. Also, computational thinking skills can change the perspective and approach to understanding a subject matter [11], [45]

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and help gain a more profound struggle to comprehend scientific concepts [18]. Weintrop et al. [36] presented several advantages of integrating computational thinking in the classroom: familiarizing students with open-ended problems, persistent working with complex issues, confidence in dealing with the complexity, representing ideas in a more meaningful way, reframing into a more organized problem, assessing the strength or weakness of the data, compiling algorithmic solutions, and checking and rearranging ambiguities in the algorithm.

III. Method

Participants

The sample was determined using the purposive sampling method. Purposeful sampling is widely utilized in qualitative research to identify and specify issues-rich cases associated with the topic of interest [46]. The participants in this study were 35 students taking introductory physics in the first semester, 29 females (83%) and six males (17%) aged 18-19 years old. The sample included relatively more female respondents than males since more females have become science-related majors in college in Indonesia. The introductory physics courses are the basis for all subsequent studies in physics. Research ethics have been carried out, and the results of this research do not affect the final assessment of students.

Research Design

This research used exploratory qualitative research to investigate students' computational thinking skills in physics. A case study is a research method that emphasizes exploration more in-depth than a description [47]. Exploratory case studies are designated to explore any phenomenon in the data which operates as a topic of interest [48]. The qualitative case method is widely used in preliminary engineering, science, and computer science learning research using a small sample [38], [49]. Being boosted by the studies, the case study was chosen since this methodology emphasizes accurate findings to investigate students' computational thinking skills profoundly with a small sample.

Furthermore, this study's participants were split into eight groups (G1, G2, G3, G4, G5, G6, G7, G8), each composed of four to five students. This group distribution ensures that students actively collaborate and participate in physics classroom learning. Collaboration promotes the input of thought, ideas, control, and reflection and provides constructive feedback to group members through rationalization and reasoning. The steps of physics learning in this study taken are 1) students are introduced to contextual issues related to kinematics problems, 2) the teacher gives examples of simple problem-solving together with students, 3) students are asked to solve the problems the teacher has passed and make simple simulation models using the Microsoft Excel program, 4) communicating accomplished solutions textually in portfolios and oral presentations.

Data Collection

Data is gathered through observation, interviews, and portfolio documents. The observation was made through a recorded Zoom cloud meeting because face-to-face classrooms cannot be implemented during the COVID-19 pandemic. Observation is an important research method in the qualitative because it is the primary step to getting actual data on the research [50]. In addition, the interviews in this study used open-ended interviews. Open interviews were chosen to obtain in-depth information about students' ideas and opinions without restricting the researcher's viewpoint. Interviews enable identifying more exact and in-depth information about an issue from the participants [50], [51]. The interview lasted approximately 30 minutes for each group. It aims to explore detailed information on the computational thinking of students. The last data source is a document. The documents collected are student project portfolios. Documents are an excellent source of textual data in qualitative research. The written document is significant evidence of understanding what the students learn, accomplish, and value [52].

Data Analysis

Data analysis in this investigation utilized the approach of Creswell [53], which consists of six stages: preparing and organizing data, exploring and coding, building descriptions and themes, representing the findings, interpreting the results, and validating the accuracy. *First*, all data are organized in file folders containing video recordings, interviews, and portfolio documents. Interview data were transcribed into data text and grouped based on the similarity of issues and ideas. *Second*, the documentary analysis was carried out by reading the students' project portfolios with the purpose was to map the students' thoughts and representations. The researchers repeatedly analyze all data, reading and observing, to get critical information about students' computational thinking in physics. The primary purpose of this analysis stage is to generate a series of essential data.

Furthermore, the resulting critical information uses to build categories that provide a broader abstraction regarding students' computational thinking. The researchers analyzed and re-analyzed to obtain valuable findings from the study and achieve the research objectives. The research data is carefully examined to determine what students' computational aspects arise in physics learning. The analysis result indicates four main characteristics of students' computational thinking in physics learning: decomposition, abstraction, simulation, and evaluation (Table 2). These findings were further validated using triangulation, theory, and other research on computational thinking in the learning context, such as in Table 1.

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Table 2. Characteristics of students' computational thinking skills in physics learning

Computational thinking skills	Indicators
Decomposition	• Problem identification
	• Representing idea
	• Formulate the problem
	• Breaking down the problem
Abstraction	• Collecting the data
	• Data analysis
	• Pattern recognition
	• Sketching/graphics
Simulation	• Iteration
	• Making algorithm
	• Manipulating data
Evaluation	• Verification
	• Troubleshooting
	• Validating
	• Debugging

IV. Results and Discussion

Results

Physics is intellectual knowledge and experience that inspires students to expand their understanding of nature and generates the basic knowledge required for future technological advancements. Integrating computational thinking in physics learning trained students to learn from mathematic formulation and solve problems by looking at data pattern recognition. This study's computational thinking skills contain multi-aspect builders that implicate cognitive complexity. The results of the data analysis of students' thinking skills indicated that students were more focused on solving problems.

Decomposition

Decomposition is an essential step to comprehending the problem. The decomposition process appeared when students investigated the critical information in the kinematic issues. The students discuss in a group and present their ideas about the facts that arise in the kinematics problems. Students looked for information based on their fundamental concepts of physics. They write down essential variables (independent and dependent variables), write the formula, and look for emerging points in the kinematics issues based on the arrangement of the ideas from their discussion. They simplify the problem by dividing it into more minor solvable problems or sub-pieces to understand the cases better. Here are some examples of students' response

"We searched for relevant variables and categorized the potential element in order of axis, structure, and function of motion" (interview, G7_NE)

"We break down the problem into simpler parts to find out which quantities and substantive elements need to solve first (Interview, G5_RI)

"We look at the issues given by the teacher step by step to find out the root of the problem." (Interview, G6_TRK)

The pieces of information that have been broken down are then grouped based on their structure, function, sequence, similarities, or characteristics and resolved in each group separately. For example (figure 1), students are grouping variables of the physical quantities in the projectile motion on the x-axis and y-axis. This activity showed students' decomposition process. Decomposition simplifies the problem by dividing it into smaller or simpler parts to make it easier to manage. Decomposition helps them find solutions more efficiently and manageably. Also, the process helps students clearly understand the goal or what they are attempting to achieve (criteria/regulations/constraints).

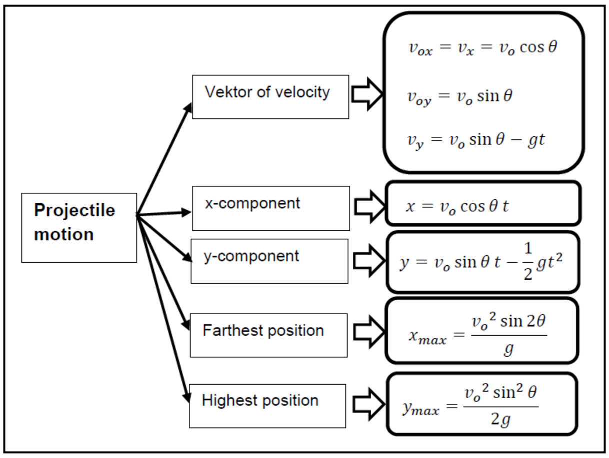

Figure 1. Example of students' answer in projectile motion

Abstraction

Abstraction is the method of describing the most fundamental aspect of problems. Abstraction is more about significant issues that are essential and not essential. The results of the analysis data indicate that the abstraction process is carried out when students identify the main problems, such as when the ball reaches the highest position and the time needed to get to the farthest places in projectile motion. They conducted the exploration process through virtual experiments of air track simulators and the PhET simulations program.

"We used the PhET simulations program to collect data virtually (interview, G1_FGL)

"We utilized an Air track simulator to gather data on time and distance (interview, G4_FF)

"We describe every state of the ball and illustrate the velocity acting on the projectile motion" (interview, G2_ KN)

Students took data, analyzed it, and looked for patterns. They described the problems based on the data collected and their prior knowledge. The data collected is

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then put into tables and analyzed to make it easier for them to get an overview or a big picture (figure 3). The abstraction process also appeared when the students looked for data patterns (pattern recognition). Data pattern recognition is conducted by sketching graphs or compiling data in tables. Some students argued that making table and graph visualization in physics is a strategic and appropriate method for analyzing information in visual display.

> *We quickly understand patterns if data analysis results are presented visually, such as graphs or charts" (interview, G8_RTS)*

> *Graphics in physics are commonplace and are widely used to look for patterns (interview, G8_IK)*

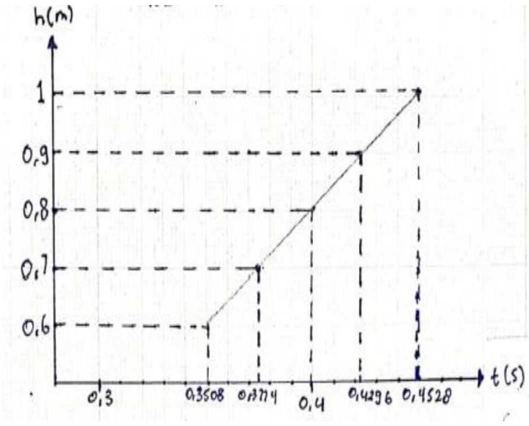

Figure 2. Example of the student's sketch of free-fall motion

The abstraction skills force learner to focus on the critical and substantive elements and assist students analyse the extent of the problem to give the right solution. This activity illustrated the students' abstraction process to understand the issues in a structured manner. In this study, students held that data and data analysis are the main points of the scientific method of physics learning.

Simulation

Modeling or simulation is not a new method in physics. Students mainly utilize simulations to understand physics concepts. The data analysis showed that students used a simulation to solve the problem. They tried to imitate data by conducting simple algorithms and programs. Students built codes and developed simple algorithms to represent data, recognize patterns, and describe physical models. They construct step-by-step instructions for solving the problem. Students realized that programming is an elaborate process that involves complex thinking that conducts computational thinking processes. They attempted to simulate, visualize data, make inferences, and predict physics phenomena. Some students stated that making simulations and models in physics pushes them to work harder.

> *"Made a physics simulation make our group work and think harder" (interview, G1_GP)*

> *"We made a simple simulation of projectile motion using Excel" (interview, G8_UG)*

> *"We made a simple algorithm of the data so that the pattern of linear motion can be noticed obviously" (interview, G4_GBL)*

In addition, students conducted data management, such as arrangement of data, filtering data, and merging. Manipulating data is undertaken to detect the pattern, assess, and prioritize tasks to find effective and efficient solutions. For example, students simulating threw a ball at different masses and angles in projectile motion. The students remarked that simulation is a way of accruing ideas, adequately building a structured thinking process, and drawing decisions appropriately in physics learning. Students realized that the existing algorithms and simulations were suitable for representing physical models in the expression of computational thinking. Figure 3 shows an example of students' simulation code using the Excel program.

> *"We sort data and manipulate mass in projectile motion simulation to assess the problem and find the right, effective, and efficient solution" (interview, G2_GLN)*

> *"Making program algorithms drives us to think in a structured thinking process" solution (interview, G6_AR)*

> *"We are merging and tinkering data to detect patterns and find the appropriate result" (interview, G7_OKN)*

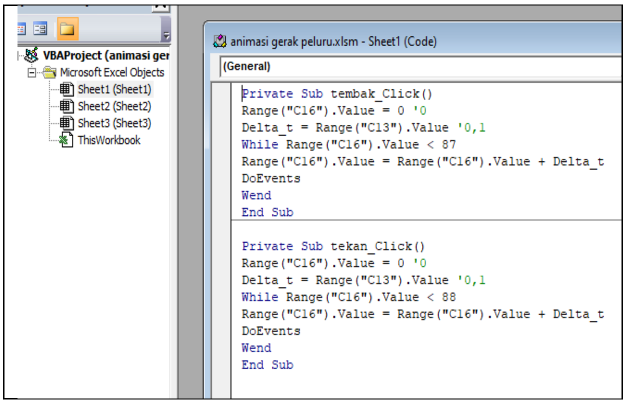

Figure 3. An example of a student's algorithm program of projectile motion

Evaluation

Evaluation is a crucial stage in computational thinking skills. In this study, evaluation refers to testing, checking, and ensuring that the solutions align with the data observation and experiment results. The evaluation process enables the algorithmic solution to be usable under various possibilities and appropriate for completing the

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problem. In this study, evaluation is necessary to highlight the benefits and drawbacks of the solution.

Students' challenge in the simulation program is accuracy in writing algorithm code. It requires checking and re-checking the code built before the running process. Data analysis indicated that evaluation is carried out by testing the simulations. They pay attention to the execution of the solution during programming. Students conducted this process to identify distinctions and appropriateness between the simulation program and the analytical data taken. This is a verification process. In addition, the student compares simulation results from other professional programs and another simulation of identical issues. Testing is one of the ways to calibrate the simulation program. In detail, students check each code or algorithm created individually to look for possible errors (debugging). The debugging process aims to analyze the program workflow and find bugs (errors) or cracks in a computer program to work as expected. If the program has trouble, they discover why the code is not running well (troubleshooting).

"We examine and check the lines per line of code that are created to look for errors in Excel" (interview, G3_ETR)

"We try to run the program and compare the results with real/ analytical data" (interview, G5_AWS)

"We used analytic data and professional programs as a reference and framework in making conclusions" (interview, G8_SO)

Furthermore, interview results indicate that students use personal experience and peers to check their programs. The ability to check individually or collectively is trained and improves the ability of students to identify and rebuild solutions in line with expectations. In short, the debugging process facilitates students to construct their knowledge and realize problem-solving strategies.

"We check each code that has been accomplished sequentially step by step in a detailed process based on our personal experience" (interview, G1_FMT)

"In the group, we check the code when an error occurs or the simulation program does not run properly" (interview, G6_HAS)

"We compared our programs with other simulations" (interview, G7_ANS)

Discussion

Within physics learning, conceptual understanding and problem-solving remain a current priority. The finding indicated four main characteristics of students' computational thinking skills in physics: decomposition, abstraction, simulation, and evaluation. Computational thinking reveals students' ability to reframe problems through basic problem-solving skills such as formulating issues, presenting an idea, finding facts, and identifying relevant physical quantities. In this study, students accessed various representations of physics concepts and tried to communicate the multiple representations based on their knowledge and understanding. They attempted to reformulate the problem to construct a thinking system that simplifies solving kinematics problems. Problem reformulation has been recognized as an initial problem-solving procedure before the beginning of computational thinking [54].

Decomposition and abstraction are essential facets of computational thinking skills. Based on the result, decomposition and abstraction help students understand and determine problem borders, restraint, purpose, and prerequisites in problem-solving. Students utilized first-order logic of thinking in defining problems based on existing facts. The decomposition and abstraction emphasize analytical logic thinking of students' problem-solving. Logical thinking enables students to construct the meaning of knowledge by analyzing and checking facts on problems clearly and precisely. Rendering points through an open, rational, and precise mindset is a logical thinking process that involves rational and intellectual design, forecasting, confirming, decision-making, and conclusions [38]. A good understanding of the problem will produce an effective and efficient solution without losing critical information.

Based on the results, students make the simulation a way to analogies and modify similar issues to find the best solutions. Analogies assist students in designing, constructing, and assessing problem solutions. Students who use analogies and modifications provide solutions using their understanding and skills related to a problem already solved [37]. Students constructed a simple simulation to explore kinematics deeply. Visual models in science can be flowcharts, computer simulations, diagrams, equations, chemical formulas, and physical models. A simulation is a form of modification and visualization of the results of thinking to make solving problems easier to understand and recognize [52]. Simulation is the expression of analytical data integrated with the ability to predict and interpret information. In this study, the simulation of a physics phenomenon trains students' thinking in a structured, step-by-step manner in script coding and frameworks to visualize and analyze problems. Also, it supports their conceptual, strategies, and procedural knowledge. Irgens et al. [24] and Sung and Black [12] posit in their research that using modifications such as simulation program builds students' thinking progress or frameworks. Unfortunately, not all students in this study have the capabilities to create an excellent coding program. They have difficulty pouring their ideas into code. Orban and Teeling-Smith [52] states that the correct set of regulations and simulation programs is often difficult for students. Creating and running programs to model some physical phenomena by engaging intuition,

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understanding, and noticing physics sets are autonomous of a mathematical formula but an iterative connection among codes and data.

Furthermore, evaluation is the last aspect of students' computational thinking skills in physics. An evaluation process is a form of reflection and validation of the program's accuracy. The result noticed that a testing process conducts the evaluation process. Testing involves multiple trials and errors to ensure and check the program. The student evaluates their solution like an iterative process. Testing and debugging are crucial when creating an algorithm or working on a computer. Debugging refers to identifying, fixing, improving solutions, investigating, and checking results. Students who can solve problems in algorithms will be able to identify, analyze, and improve the solutions offered systematically and efficiently [55]. In this study, students' systematic testing and debugging contributed to problem-solving, primarily when evaluating and considering potential solutions. Evaluation in simulation programs reinforces and strengthens students' idea that computer programs represent rational thinking of accuracy and reliability.

Integrating computational thinking in physics learning helps students construct their knowledge and allows them to determine the best solution to resolve the problem. Bers et al [54] asserted that students could learn more deeply when constructing their knowledge through a project in a community of learners. Students are trained in open-ended physics problems by examining various perspectives involving graphs, tables, and mathematics. Open-ended problems have opportunities to utilize knowledge and skills comprehensively [56]. Students have much experience finding solutions to the problem, such as simulation. Computational thinking assists and develops physics students' accuracy, structured thinking, brainstorming, and a framework of difficulties to obtain an effective and efficient solution. Students use their logical reasoning when determining solutions. This logical reasoning is the key to solving a problem in physics learning. It helps them solve issues precisely based on data dan simulation.

Furthermore, this study has limitations; it only focuses on the kinematics concept and has a restricted number of participants. The challenge when integrating computational thinking skills in the school is teachers' ability concerning computer science. Teachers have to upgrade their computer science skills and knowledge. Future research must investigate other physics concepts like waves, magnetism, and atoms. Also, future studies need to follow up by considering the computational attitudes of students.

V. Conclusion

The main point of computational thinking is problem-solving. This study indicated four primary characteristics of students' computational thinking skills in physics: decomposition, abstraction, simulation, and evaluation. Computational thinking improves students' ability to problem understanding, identify problem boundaries constraints and set goals and prerequisites for problem-solving in physics learning. It develops students' ideas and logical reasoning more structured when determining solutions and evaluating problem-solving frameworks. Also, computational thinking skills in physics learning allow students to develop relevant ideas through their collaborative problem-solving experience. This study illustrates that to understand physics, students not only learn physics from a series of mathematical formulas but based on pattern recognition of the data. This research is expected to contribute to physics teachers integrating computational mental skills in their learning classroom. Integrating computational thinking in learning will train students to be responsive to open problems and think logically and structurally.

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Declarations

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