Constructivist Digital Learning: Integrating APOS and RME for Computational Thinking Development in Higher Education

Trisnawati [1, a)], Sugeng Sutiarso [2, b)], Rangga Firdaus [3, c)], and Tina Yunarti [2, d)]

[1] *Department of Education, Faculty of Teacher Training and Education, Universitas Lampung, Bandar Lampung, Indonesia*
[2] *Department of Mathematics Education, Faculty of Teacher Training and Education, Universitas Lampung, Bandar Lampung, Indonesia*
[3] *Department of Educational Technology, Faculty of Teacher Training and Education, Universitas Lampung, Bandar Lampung, Indonesia*

[a)]Corresponding author: trisnawatistmikpsw@gmail.com
[b)]sugeng.sutiarso@fkip.unila.ac.id
[c)]ranggafirdaus@fkip.unila.ac.id
[d)]tina.yunarti@fkip.unila.ac.id

Abstract. Digital learning has become a core component of higher education worldwide. Yet, its implementation often relies on behavioristic approaches emphasizing stimulus–response patterns, repetitive drills, and outcome-focused assessments. Such models frequently position students as passive recipients of information, offering limited opportunities to develop higher-order thinking skills, particularly computational thinking (CT). This study introduces a constructivist digital learning model integrating APOS theory (Action, Process, Object, Schema) and Realistic Mathematics Education (RME) to actively engage students in knowledge construction. The model was developed through a research and development (R&D) approach, utilizing the Waterfall design framework, which comprises systematic stages of needs analysis, design, development, implementation, and evaluation. Empirical findings from a limited trial with university students demonstrated a significant improvement in CT skills (average gain score = 0.65, $p < 0.05$), increased student engagement (87.5% reported learning as more meaningful and interactive), and deeper conceptual understanding as students successfully connected mathematical concepts with real-life contexts. Qualitative data further revealed students' cognitive progression through APOS stages supported by RME-based tasks and digital scaffolding. By addressing methodological rigor and incorporating critical analysis, this study presents a theoretically grounded and empirically validated digital learning design that transcends behavioristic paradigms. It provides practical guidance for developing student-centered, technology-enhanced learning environments that align with the demands of 21st-century education.

Keywords: APOS; computational thinking; constructivist learning; RME

INTRODUCTION

The development of information and communication technology over the past five years has brought major changes to higher education worldwide. The presence of digital learning platforms such as Learning Management Systems (LMS), video conferencing applications, and Massive Open Online Courses (MOOCs) has transformed the way lecturers and students interact, access materials, and manage the learning process (Zou, Kuek, Feng, & Cheng, 2025). These innovations provide flexibility in terms of time and place, offer access to a wide range of learning resources, and enable personalized learning tailored to students' needs. This transformation accelerated when the COVID-19 pandemic forced higher education institutions to adopt fully online learning, even though the transition often occurred without significant changes to the underlying learning paradigms (Zou et al., 2025). Although digital learning infrastructure has advanced rapidly, its implementation is still often dominated by a behaviorist approach. This model focuses on providing stimulus and response, as well as repetitive drills, and evaluation that emphasizes only the final results (Shanker Rao & Bhagat, 2024). In behaviorist-based digital learning, students tend to be passive recipients of information. Materials are typically delivered linearly through lecture videos or online presentations, followed by automated quizzes that assess right or wrong answers without providing room for deeper exploration of concepts. While this practice is effective for training simple procedural skills, it is insufficient for developing higher-order thinking skills, especially computational thinking (CT) (Zhang, Mirzaei, Mouza, Pollock, & Guidry, 2025).

Computational thinking is an essential 21st-century skill that comprises four main components: breaking down problems into smaller parts (decomposition), recognizing recurring patterns (pattern recognition), identifying the core problem through abstraction, and designing systematic steps to solve the problem (algorithm design) (Zhang et al., 2025). This skill is important not only in computer science but also in solving complex problems across various disciplines. Unfortunately, the behaviorist approach that dominates current digital learning offers limited opportunities for students to optimally practice CT. Evaluations that solely measure final outcomes make it difficult for students to understand the connection between the concepts they learn and their real-world applications (Shanker Rao & Bhagat, 2024). Recent studies reveal that although CT is increasingly discussed in higher education literature, its implementation often remains limited to programming courses and is not fully integrated into non-ICT disciplines (Grizioti, 2025). Behaviorist digital learning models reinforce this gap by overlooking the need for students to actively construct knowledge. The OECD report (2025) also emphasizes that digital learning should not merely transfer content to an online platform but should leverage technology to enhance thinking processes, collaboration, and independent learning.

To address these issues, the constructivist approach offers a more suitable solution. Constructivism views learning as an active process in which students build their own knowledge through interaction with problems, environments, and experiences. In this context, APOS Theory (Action, Process, Object, Schema) provides a framework for understanding how mathematical and scientific concepts develop from concrete actions toward an integrated, abstract understanding (Asiala et al., 1996). Theoretical relevance remains, although the initial publication is beyond the past five years. This theory emphasizes that students need to go through stages of acting, processing actions into mental processes, viewing concepts as objects, and ultimately integrating these concepts into a broader knowledge schema. This approach can be strengthened through Realistic Mathematics Education (RME), which focuses on using real-world contexts as the starting point for learning (Gravemeijer & Cobb, theoretical relevance). By using realistic contexts, students can understand concepts through problems closely related to their lives, making learning more meaningful. When APOS and RME are integrated into digital learning, students not only understand concepts gradually and systematically but can also relate them to real situations. This integration naturally fosters CT development, as students engage in activities such as breaking down contextual problems, recognizing patterns in data or events, abstracting core concepts, and designing algorithmically implementable solutions. Several recent studies support the effectiveness of constructivist digital approaches. Zou et al. (2025) report that digital learning models positioning students as active agents in knowledge construction increase engagement, conceptual understanding, and long-term learning retention. Zhang et al. (2025) also found that integrating exploratory and collaborative activities in digital learning significantly improves CT skills across disciplines. Grizioti (2025) adds that CT learning, when freed from the constraints of traditional programming and linked to real-world contexts, is more effective in enhancing cross-disciplinary problem-solving skills.

Based on this background, this study aims to achieve four primary objectives. First, to design a constructivist digital learning model that integrates APOS Theory and RME to enhance students' CT. Second, to develop an interactive, contextual digital learning product in line with constructivist principles. Third, to test the model's effectiveness through limited field trials, focusing on improving conceptual understanding and CT. Fourth, to collect and analyze students' and lecturers' responses regarding the applicability, engagement, and relevance of this model in the digital education era. This study is expected to make a theoretical contribution to the development of digital learning models oriented toward 21st-century skills, as well as a practical contribution in the form of digital learning design guidelines that can be widely implemented. Furthermore, it may serve as a strategic effort to shift the digital learning paradigm from behaviorist dominance toward a constructivist model that encourages students to think critically, creatively, and computationally.

LITERATURE REVIEW

Digital Learning Approaches: Behaviorist and Constructivist

The development of digital learning in higher education has given rise to various pedagogical approaches. The behaviorist approach, which focuses on stimulus–response relationships, repetitive practice, and outcome-based evaluation, remains the dominant approach on most online learning platforms. While effective for mastering procedural skills, this model often turns students into passive recipients of information, thereby limiting opportunities to develop higher-order thinking skills (Zhang et al., 2025). In contrast, the constructivist approach emphasizes the active role of students in building knowledge through interaction with problems, discussions, and reflection, which has been proven to enhance conceptual understanding and critical thinking skills (Suprapti et al., 2023).

Computational Thinking (CT) as a 21st-Century Skill

CT has become one of the essential 21st-century skills as it encompasses the ability to break down complex problems into smaller parts (decomposition), recognize patterns (pattern recognition), simplify concepts (abstraction), and design systematic steps to solve problems (algorithm design). Recent studies indicate that CT is not only relevant in programming courses but also in other disciplines that require problem-solving skills and logical reasoning (Shanker Rao & Bhagat, 2024). Integrating CT into various learning contexts can help students connect theoretical concepts with real-world applications.

Effectiveness of the Constructivist Approach for CT Development

A number of studies have shown that constructivist-based learning provides greater opportunities for students to sharpen their CT skills. For example, Suprapti et al. (2023) found that students participating in project-based constructivist learning in mathematics education showed significant improvement in CT skills, particularly in decomposition and abstraction. This approach encourages students not only to memorize procedures but also to understand concepts deeply and flexibly.

APOS, RME, and Digital Integration

In this study, Piaget's theory, APOS, and Realistic Mathematics Education (RME) are integrated within a constructivist framework to strengthen students' conceptual understanding of mathematics. Piaget describes stages of cognitive development from concrete to formal, emphasizing the construction of knowledge through assimilation and accommodation processes (Piaget, 1977). The APOS theory maps conceptual understanding through stages of action, process, object, and schema (Dubinsky & McDonald, 2001), while RME emphasizes context-based learning that guides students from informal reasoning to formal abstraction through the process of mathematization (Gravemeijer & Doorman, 1999). Figure 1 illustrates the integration.

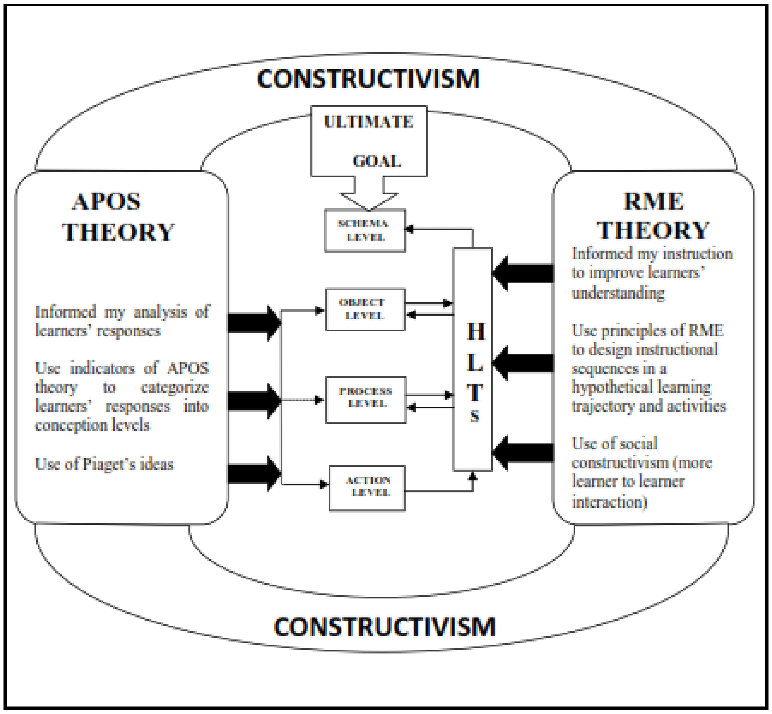

FIGURE 1. Integration framework

This integration enables learning to begin with situations relevant to students, then progress toward abstract concepts, utilizing APOS to analyze their level of understanding. Technologies such as GeoGebra and MATLAB are utilized to visualize abstract concepts, support cognitive transitions from action to schema, and present realistic contexts that enhance motivation and engagement (Maury, 2024; Tong et al., 2022; Tuktamyshov & Gorskaya, 2024). This approach not only targets the mastery of technical skills but also bridges the gap between informal knowledge and formal mathematical structures, enabling students to gradually connect concepts to real-world phenomena and be prepared to face challenges in the digital era. RME is grounded in the use of real-life contexts as the starting point for mathematics learning. With the aid of digital technology, RME can be implemented more interactively. Kutluca and Akran (2025) developed an RME learning model based on digital tools that allows students to explore mathematical concepts through simulation and visualization. Integrating RME into digital learning can strengthen the connection between abstract concepts and everyday life phenomena.

RESEARCH METHODOLOGY

Research Design

This study employed a Research and Development (R&D) approach to design, develop, and evaluate a constructivist digital learning model integrating APOS Theory and Realistic Mathematics Education (RME) to enhance computational thinking (CT) among undergraduate students. The Waterfall model (Pressman & Maxim, 2021) was selected for its sequential and systematic nature, ensuring that each phase—from needs analysis to evaluation—was completed before proceeding to the next stage. This approach was chosen because it allows structured development, systematic validation, and empirical testing of educational innovations. Compared to iterative models such as Design-Based Research (DBR) or ADDIE, the Waterfall model provides clearer documentation and evaluation checkpoints, which are crucial when the aim is to develop a tested prototype ready for wider implementation (Balaji & Murugaiyan, 2022; Ramírez-Montoya et al., 2024).

R&D Stages

The R&D procedure followed five sequential stages, summarized in Table 1.

TABLE 1. Research stages, activities, and data collected

Stage	Main Activities	Data / Instruments
Needs Analysis	Observations of existing teaching practices, interviews with lecturers and students, curriculum analysis to identify needs and learning gaps	Observation checklist, interview guides, curriculum review sheets
Design	Developing the digital learning module blueprint integrating APOS–RME principles; expert validation of content and instructional design quality	Module design documents, expert validation forms
Development	Building the module on LMS (Moodle); integrating simulations, contextual videos, and digital worksheets	Prototype module files, pilot usability feedback
Implementation	Conducting limited trial with 32 students of the Information Systems Program at Institut Bakti Nusantara; administering pre-test, post-test, and questionnaire	Context-based CT test, learning engagement questionnaire, classroom observation notes
Evaluation	Analyzing learning outcomes quantitatively and qualitatively; refining the model based on results and expert feedback	Statistical reports, interview transcripts, observation data

Research Participants

Participants were 32 undergraduate students enrolled in the Information Systems Program, Institut Bakti Nusantara. Purposive sampling was employed to ensure that participants possessed basic digital literacy skills and were enrolled in courses that incorporated problem-solving and computational thinking components (Suprapti et al., 2023).

Research Instruments

In this study, three different instruments were utilized. The first instrument was a Context-Based Computational Thinking Test, which consisted of 10 open-ended tasks designed to evaluate four computational thinking indicators: decomposition, pattern recognition, abstraction, and algorithm design (El-Hamamsy et al., 2023). To ensure the test's clarity, relevance, and alignment with the research objectives, its content validity was reviewed by three experts in mathematics education and computing. Reliability was assessed using Cronbach's alpha, with a value of $\alpha \geq 0.70$ regarded as acceptable for internal consistency (Gliem & Gliem, 2003).

The second instrument, the Learning Engagement Questionnaire, was adapted from Suprapti et al. (2023) and measured behavioral, emotional, and cognitive engagement on a 5-point Likert scale. Construct validity for this questionnaire was examined through Exploratory Factor Analysis (EFA), while internal consistency was verified with Cronbach's alpha.

The third instrument consisted of observation sheets and interview protocols. Observation sheets were used to document student collaboration, participation, and how students utilized the digital learning module. Semi-structured interviews were conducted to gain insights into students' experiences, perceived benefits, and challenges with the

APOS–RME-based digital learning module. For the qualitative data, inter-rater reliability in coding was calculated using Cohen's Kappa.

Data Analysis

Data will be analyzed through a combination of quantitative and qualitative methods. For the quantitative aspect, normality tests such as the Shapiro–Wilk test will be performed prior to conducting any parametric analyses. A paired sample t-test will then be used to compare students' computational thinking scores before and after the intervention, and the magnitude of change will be measured using effect size calculations, such as Cohen's d (Zhao et al., 2025). On the qualitative side, interview and observation data will undergo thematic analysis, following the approach outlined by Braun and Clarke (2006). This analysis will involve three coding phases: open coding, axial coding, and selective coding. To enhance the trustworthiness of the findings, results will be triangulated across test scores, interviews, and observational data (Otto et al., 2024).

RESULTS AND DISCUSSION

Model Description

The digital learning model developed in this study integrates two main approaches: APOS Theory (Action, Process, Object, Schema) for the cognitive stage framework, and Realistic Mathematics Education (RME) for the selection and management of learning contexts. This integration aims to create a constructivist learning experience in which students not only receive material but also actively construct their understanding through interaction with real-world contexts.

The learning module is presented in an interactive format through a Learning Management System (LMS), incorporating a variety of media and supportive features to enhance the educational experience. Among these features are GeoGebra simulations, which play a key role in helping students visualize mathematical concepts, especially those related to vector representation and operations. Through these simulations, learners are empowered to independently investigate and deepen their understanding of mathematical ideas. An overview of the different types of GeoGebra applications used is provided in Figure 2.

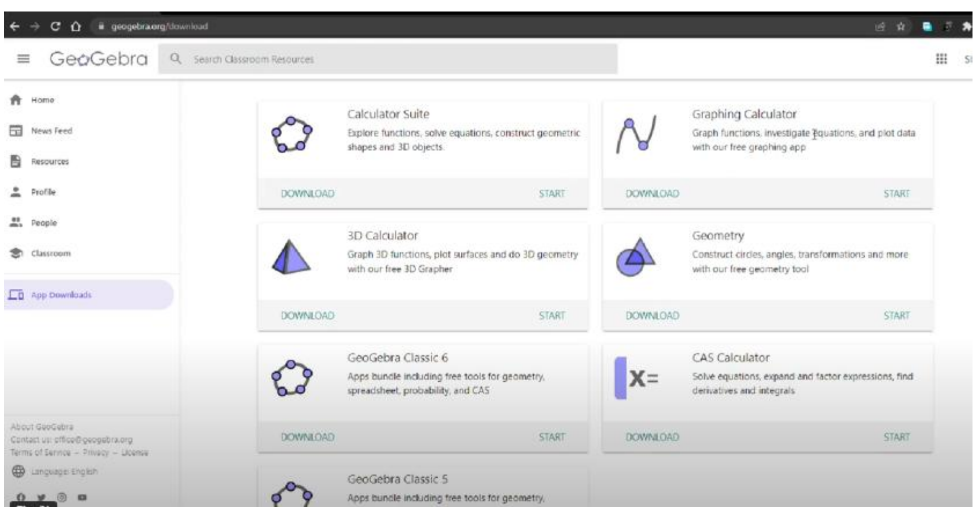

FIGURE 2. GeoGebra app types

The contextual learning videos provide explanations of material that connect mathematical concepts to real-world scenarios, such as flight navigation, drone movement, and spatial data analysis. Figure 3 presents a sample of this type of video.

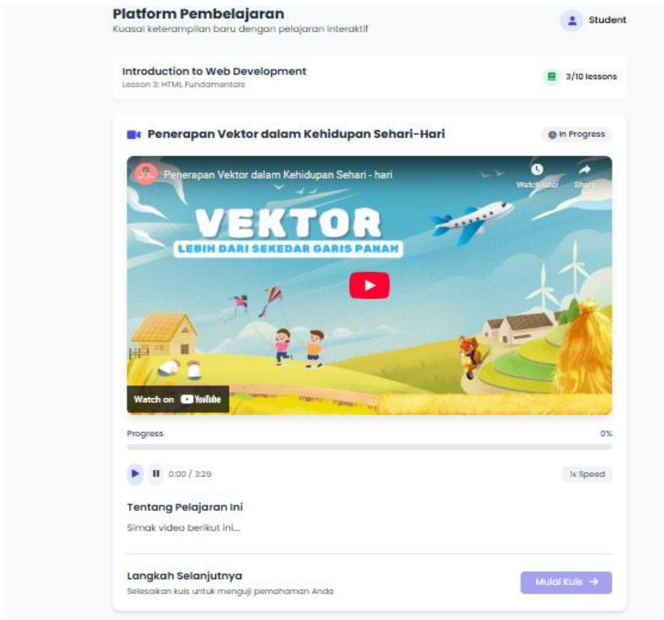

FIGURE 3. Video example

Digital Student Worksheets (LKM) feature context-based tasks designed to guide students through processes such as problem decomposition, pattern recognition, abstraction, and algorithm design. Figure 4 provides an example of these worksheets.

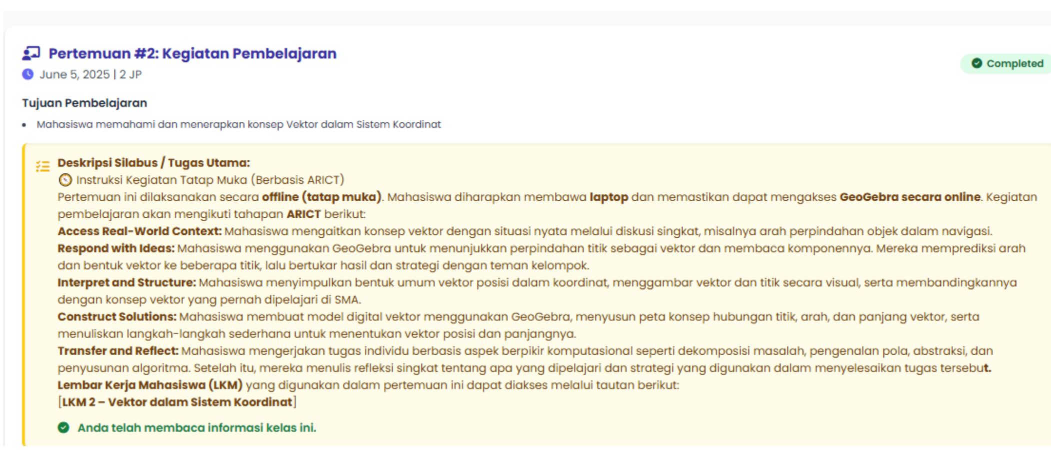

FIGURE 4. LKM example

The collaborative discussion forums provide students with a dedicated space to share ideas, compare various problem-solving methods, and deepen their understanding through group interaction. Figure 5 illustrates the forum dashboard.

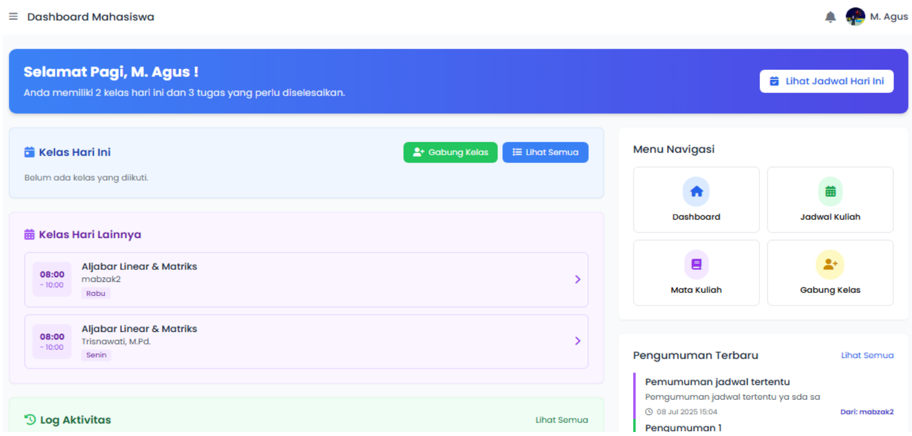

FIGURE 5. Collaborative forum example

This model is designed to support all components, making learning more meaningful, structured, and aligned with the development of computational thinking skills.

Trial Results

A limited trial involving 32 students of Mathematics Education demonstrated notable gains in computational thinking (CT) skills and learning engagement. Statistical analysis revealed a significant increase in CT scores, with an average gain of 0.65, considered medium to high, across all indicators, including problem decomposition, pattern recognition, abstraction, and algorithm design.

Additionally, 87.5% of students reported that the learning experience was more meaningful than previous digital lectures, attributing their increased motivation and active participation to the use of real-world contexts, interactive simulations, and collaborative discussions.

Interviews and worksheet analyses further showed that students could clearly explain the links between mathematical concepts and their real-world applications, providing accurate examples of vectors in navigation, mapping, and object movement analysis. These results suggest that the APOS–RME-based digital learning model not only enhances CT skills but also strengthens student engagement and conceptual understanding.

Discussion

The findings demonstrate that integrating APOS Theory and Realistic Mathematics Education (RME) into a constructivist digital learning model effectively enhances computational thinking (CT) skills, student engagement, and conceptual understanding. Beyond confirming previous studies (Zhao et al., 2025; Otto et al., 2024), the results provide deeper insights into how the cognitive stages of APOS unfold within real-world contexts, as facilitated by RME, thereby shaping students' problem-solving processes.

First, the significant improvement in CT scores (gain score = 0.65) reflects not only better problem-solving outcomes but also reveals the cognitive transitions students underwent. Observational and interview data illustrate how students initially engaged at the Action stage by manipulating concrete objects or digital simulations, for example, plotting drone movement vectors on GeoGebra. As one student explained during the post-lesson interview:

> *"At first, I just tried to follow the instructions to move the drone on the screen. But after discussing with my group, I realized there was a pattern in the direction and distance that could be written as a formula."*

This progression marks the shift from Action to Process, where students began internalizing the problem structure rather than merely executing steps. The Object stage emerged when students began referring to "the vector equation" or "the algorithm" as a single entity they could mentally manipulate. Finally, reaching the Schema stage, students integrated multiple vector concepts to design navigation algorithms for different scenarios, demonstrating higher-order abstraction and algorithmic thinking.

Second, the RME component provided authentic contexts, such as navigation, mapping, and logistics, that anchored these APOS stages in meaningful problems. Students reported that working on real-life cases made abstract mathematical ideas "less intimidating" and "easier to connect with programming logic," as expressed by another participant:

> *"It wasn't just about solving math exercises. We had to think like we were planning a real delivery route using vectors. That made the math part feel more like problem-solving than memorization."*

This interplay between realistic contexts (RME) and structured cognitive stages (APOS) appears crucial for sustaining engagement and fostering systematic CT development. Moreover, the use of interactive modules (GeoGebra simulations) and digital student worksheets (LKM) functioned as scaffolding tools guiding students through these transitions. Such scaffolding aligns with studies emphasizing that well-sequenced digital tasks support metacognitive reflection and collaborative interaction, both of which are essential for developing computational thinking (Otto et al., 2024).

Lastly, linking the findings to the FADE-CTP framework (Adorni et al., 2024) highlights the need for task design precision. Each learning activity must explicitly target one or more CT competencies while facilitating movement through APOS stages. The empirical evidence here suggests that contextual realism (RME) combined with cognitive structuring (APOS) creates a synergistic effect, leading to deeper conceptual understanding and transferable problem-solving skills.

Overall, this constructivist digital learning model demonstrates both theoretical and practical advantages over the traditional behaviorist approach. While behaviorism has proven effective for procedural drills, it falls short in nurturing the higher-order thinking skills required in the 21st century. In contrast, the APOS–RME integration fosters systematic problem-solving, conceptual understanding, and authentic engagement, as evidenced by the significant gains in computational thinking (CT) scores and high levels of student participation. Practically, this model offers a replicable framework for educators seeking to redesign digital learning environments toward a constructivist paradigm. For example, integrating the model into flipped classrooms or hybrid learning settings enables students to engage with contextual problems asynchronously, refining their understanding through collaborative discussions. This aligns with Turyamureeba's (2024) findings, which show that constructivist-based blended learning models, such as rotation and flipped approaches, enhance both student participation and academic satisfaction.

Moreover, embedding learning analytics into the LMS platform can provide real-time feedback on students' CT development, enabling adaptive scaffolding tailored to individual learning needs. Training programs for lecturers should also be developed to ensure they can effectively manage digital platforms, facilitate collaborative problem-solving, and integrate authentic contexts into learning activities. From a policy perspective, adopting this model at the institutional level supports the transition toward outcome-based education emphasizing critical and creative thinking, digital literacy, and computational competencies. For researchers, the model presents opportunities to investigate the long-term effects on students' higher-order thinking skills across disciplines, providing a rich field for future empirical studies.

CONCLUSION AND RECOMMENDATIONS

Conclusion

This study developed a constructivist digital learning model that combines APOS Theory and Realistic Mathematics Education (RME) to enhance computational thinking (CT) skills in higher education students. Using a five-stage Research and Development process based on the Waterfall model, the approach included needs analysis and effectiveness evaluation.

Trial results revealed significant improvement in CT, with an average gain score of 0.65 (medium–high category) and a p-value less than 0.05. Student engagement increased, with 87.5% of respondents finding the learning more meaningful, interactive, and relevant to real-world contexts. Additionally, students demonstrated a deeper conceptual understanding by connecting mathematical concepts to real-life situations, aligning with the principles of contextual learning. The integration of APOS cognitive stages and RME contexts fostered systematic, reflective, and creative thinking throughout the instructional design.

Recommendations

Based on the research findings, it is recommended that the model be implemented on a wider scale across various institutions and study programs to evaluate its generalizability. The integration of adaptive learning technologies and analytics within LMS platforms is suggested to enable real-time feedback and personalized learning experiences. Extending the APOS–RME model to disciplines beyond mathematics, such as science, engineering, economics, and technology, could further assess its effectiveness in fostering computational thinking in diverse contexts. Structured professional development for lecturers should be provided to support digital pedagogy, collaborative facilitation, and context-based instructional design. Finally, future research should focus on examining long-term retention of computational thinking skills, comparing the model with other teaching approaches, and investigating its impact on students' critical and creative thinking over time.

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