ComputUp: A Digital Board Game Framework for Enhancing STEM Education

Jon-Chao Hong, Yu-Ting Tu*, Chi-Chin Wong

***Abstract*—This paper introduces *ComputUp*, a digital board game designed to foster computational thinking (CT) and enhance STEM education through arithmetic-driven gameplay and interdisciplinary Chance card challenges. Unlike traditional chance-based games, *ComputUp* requires players to generate their own movement through strategic calculations, promoting mathematical reasoning and problem solving. The game integrates CT components such as decomposition, pattern recognition, abstraction, and algorithmic thinking into its core mechanics. Chance challenges are drawn from science, history, and practical knowledge domains, encouraging cross-curricular learning and real-world application. With features that support both individual and collaborative play, as well as built-in analytics to support formative assessment, *ComputUp* serves as a versatile educational tool for classroom and extracurricular STEM learning, and for team building.**

***Index Terms*—Computational thinking, Educational app, Game-based learning, STEAM education, Team building.**

I. Introduction

In recent years, the integration of computational thinking (CT) into science, technology, engineering & mathematics (STEM) education [1] and the use of digital educational games [2] have become two of the main foci for educators and researchers seeking to enhance player engagement in today's fast-evolving technological landscape. While Sharma et al. [3] focused on teacher-facing tools, their findings underscore the critical role of theoretically grounded design, such as that embodied in curriculum frameworks, in shaping the acceptance of game-based learning. These insights further emphasize the pedagogical value of well-structured educational tools such as *ComputUp* in promoting engagement and building learner confidence. Developed by integrating arithmetic strategies, interdisciplinary Chance card challenges, and team collaboration mechanisms with the four core elements of CT, *ComputUp* addresses three persistent problems in gamified learning: the imbalance between entertainment and cognitive depth, the separation of CT and disciplinary knowledge, and the absence of a collaborative dimension. In particular, it transforms arithmetic exercises and interdisciplinary quizzes into interactive opportunities for problem solving, strategic reasoning, and cross-domain learning.

This study demonstrates how mechanism design, data tracking, and collaboration models can be combined to create an evaluable, scalable, and customizable framework for cultivating CT. The paper presents the design, theoretical framework, and educational implications of *ComputUp*, highlighting its potential to enhance STEM learning through immersive, structured play.

II. Theoretical Background

A. Game-Based Learning

Game-based learning (GBL) has emerged as a powerful pedagogical strategy for enhancing cognitive and affective outcomes in STEM education, particularly by fostering higher-order thinking skills such as analysis and evaluation [4,5]. *ComputUp* was developed with these principles in mind, integrating arithmetic gameplay with subject-specific quizzes to promote computational thinking and interdisciplinary learning. Each decision-making moment in the game, along with the information available to players, forms its cognitive foundation, requiring them to process symbolic rules under time pressure or competition [6,7]. While overly entertaining games may hinder reflection, overly didactic ones may reduce engagement [8]. Thus, striking a balance between fun and learning remains a core challenge in educational game design. *ComputUp* addresses this by offering a customizable, engaging experience that supports both motivation and deep learning.

B. Computational Thinking in STEM

The integration of CT into STEM education has gained increasing attention in recent years, as STEM subjects provide rich contexts for developing CT, while CT, in turn, enhances learners' understanding of STEM content through structured reasoning and problem-solving processes [9]. Prior studies have suggested that incorporating CT into competitive or game-based learning environments can enhance engagement and foster CT skills [10, 11]. However, most existing CT educational games focus on programming environments (e.g., Scratch) or single-player puzzle-solving (e.g., CodeCombat). Although effective for cultivating algorithmic thinking, these approaches generally lack: (1) in-depth integration with mathematics and science knowledge; (2) collaboration and strategic game mechanisms; and (3) formative assessment data support. *ComputUp* addresses these gaps through arithmetic-driven movement, interdisciplinary Chance cards, and team strategic collaboration, offering a promising pathway for innovative instructional design. In addition, *ComputUp* is designed around the four elements of CT proposed by Wing (2006), namely decomposition, pattern recognition, abstraction, and algorithms, which

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are systematically mapped to specific gameplay features in Section III.

III. Game Design: *ComputUp*

A. *The Features*

ComputUp is a cross-platform educational game available on both iOS and Android systems. Designed as a digital board game, it draws on the notion that symbolic rule processing enhances higher-order cognition [6], and the finding that task decomposition reduces cognitive load [12], replacing traditional dice rolls with arithmetic-driven movement. The design choice strengthens mathematical reasoning while simultaneously fostering strategic decision-making. The four core components of CT are purposefully embedded into the game's mechanics, with each round prompting players to engage in structured reasoning, strategy formulation, and problem solving. Rounds conclude with a STEM-related Chance challenge, and correct responses earn in-game coins. These coins can be used to customize a personal aquarium—a feature that promotes creativity and reinforces interdisciplinary engagement beyond the core gameplay. Through this design, arithmetic becomes a means of cultivating CT, rather than merely a subject of rote calculation.

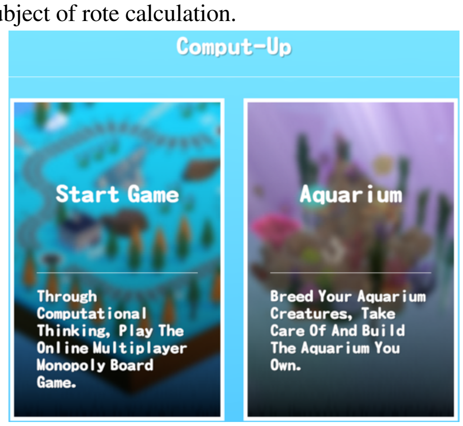

Fig. 1. Main menu: *ComputUp*'s home screen displaying access to the main game and aquarium features.

B. *Core Game Mechanism Design*

1) Game Setup

Players create game rooms with adjustable settings: number of players (up to 6), team modes (1v1, 2v2, all the way to 2:2:2), number of operand cards (2–5), total steps to the goal (125–500), subject domain for Chance card questions, win conditions, use of negative numbers, and difficulty level adjustments.

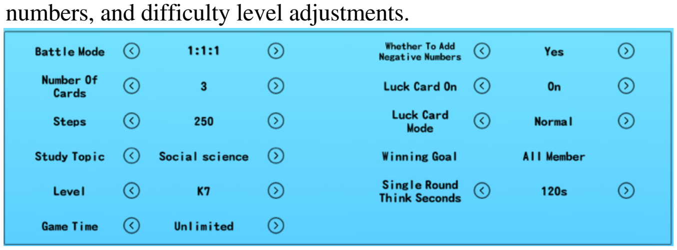

Fig. 2. Game room setup page displaying available configuration options.

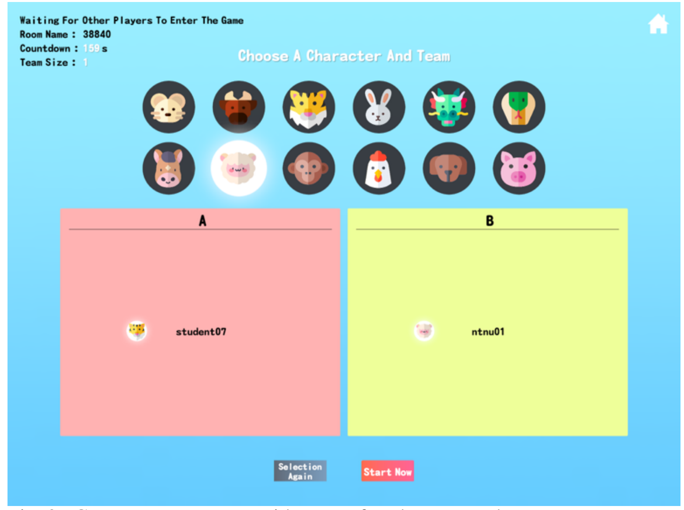

Fig. 3. Game entrance room with avatar for players to select.

2) Arithmetic Strategies and CT mapping

Each round begins with players drawing number cards—red for positive and blue for negative values. Players compute the optimal expression to maximize movement or trigger strategic effects such as shortcut access or bumping opponents.

For example, in Figure 4, the drawn numbers are 6, -9, and 7. Players can use these cards to maximize movement, reach a shortcut, or cause a drawback for an opponent; possible expressions include:

- $7 \times 6 + (-9) = 33$ steps
- $6 - 7 \times (-9) = 69$ steps

A miscalculation such as $6 - 7 \times (-9) = 9$, shown in red in Figure 5, indicates an incorrect answer. Since there are no trigger tiles in this round, the optimal move is the highest valid result: 69 steps.

Each arithmetic operation simultaneously exercises core CT constructs. Task decomposition appears when players break the problem into subtasks to manage cognitive load and test conditional strategies [12]. Abstraction occurs as they compare solution paths and eliminate irrelevant information to reach an efficient outcome [13]. Designing and adapting multi-step expressions represent algorithm construction [14], while flexible card selection demonstrates use of variables [15, 16]. Recurrent card combinations highlight pattern recognition [17].

Through this integration, arithmetic becomes a vehicle for CT cultivation, transforming symbolic manipulation into purposeful reasoning and decision-making.

Fig. 4. Calculation section, showing the start of a round with number cards in the bottom-left interface, sample equations with visual feedback on

correctness, a communication tab for teammates, and number cards selected at the entrance.

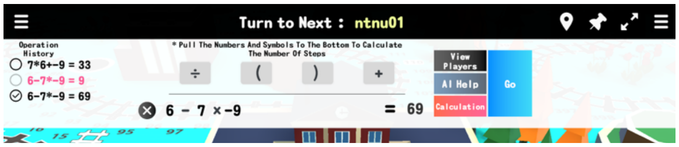

Fig. 5. Calculation section closeup, showing results in entry order, with correct answers displayed in black and incorrect answers in red. A correct result indicates the number of steps a player can move if selected, while the calculation table allows players to either compute the result manually or spend game coins to request AI assistance.

3) Chance Card

After submitting a valid arithmetic expression, players select a Jack, Queen, or King card to initiate a Chance challenge. Each card indicates an ascending difficulty tier and offers 10, 20, or 30 steps as rewards. By embedding progressive complexity consistent with Cognitive Load Theory [18], this mechanism balances challenge and ability. Correct responses not only allow accuracy but also introduce strategic decision-making, as players may advance their own pawn, support a teammate, or set back an opponent.

To enhance immersion and human-computer interaction, the Chance challenges involve interactive interfaces: Jack cards use standard tap interaction to gain 10 steps, Queen cards involve swiping away virtual sand to gain 20 steps, and King cards require blowing into the device to clear leaves and gain 30 steps. Additionally, ComputUp integrates interdisciplinary content through Chance card questions categorized as Facts & History for J cards, Function & Effect for Q cards, and STEM Knowledge for K cards, fostering both knowledge application and cross-curricular learning. This structure transforms a simple challenge-response interaction into a cognitively demanding, interdisciplinary learning experience.

Fig. 6. Chance card selection in the *ComputUp* game round, showing the selection screen where players draw Jack (J), Queen (Q), or King (K) cards to determine bonus question difficulty and point values of 10, 20, or 30 steps. A sample J-card multiple-choice question in Mandarin is displayed to assess cultural or historical knowledge, with players required to choose the correct answer to earn bonus movement steps. A 30-second countdown timer is provided for answering the question, shown here at 24.3 seconds.

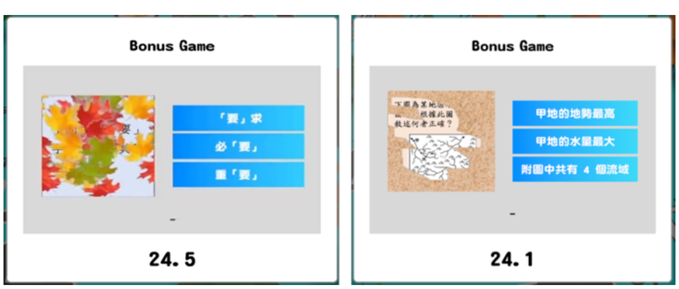

Fig. 7. Human–device interaction in the *ComputUp* game, showing the K-card interface where players blow away leaves and the Q-card interface where they swipe away sand to reveal a Chance card question with multiple-choice options.

4) Domain Knowledge

Each type of Chance card is designed to target a specific knowledge category: J (Jack) cards focus on factual and historical knowledge, Q (Queen) cards emphasize functional understanding and effects, and K (King) cards cover STEM-related concepts. Below are sample questions from each category:

- Jack card questions (Facts & History):
  Q: Completed in 1882 and named to honor Canadian support, what was this training base called?
  A: (A) Lixuetang Academy
  Q: Which location, situated at the northern mouth of the Tamsui River, was once called the "Venice of the East" and served as a key port for Western influence in northern Taiwan.
  A: (C) Tamsui
- Queen card questions (Function & Effect):
  Q: Which is not a function of a sky lantern?
  A: (C) To signal enemies
  Q: Which of the following is the primary function of a reservoir?
  A: (B) Power generation, irrigation, water storage, water supply
- King card questions (STEM Knowledge):
  Q: Iron ions turn yellow-brown in the Yin-Yang Sea due to what process?
  A: (A) Oxidation
  Q: The area of the Erchong Flood Diversion Channel is 424 hectares. How many "gong mu" (a unit of area) is that equal to?
  A: (B) 42,400 gong mu

5) Gamification

This structure transforms a challenge-response format into an interdisciplinary, cognitively demanding learning opportunity. Specifically, the Chance challenge system allows players or instructors to embed custom learning and training content as gamified experiences, allowing trainees or students to learn through play.

6) The Condition to Win the Game

The game concludes when a player lands precisely on the final step; overshooting triggers a bounce-back mechanism, adding a layer of complexity to the endgame strategy. *ComputUp*'s team modes embody principles of Positive Interdependence Theory [19] and Group Goal Structure Theory [20], where group success depends on shared progress. The cumulative step system enables players to contribute earned steps toward teammates, fostering reciprocity and collective responsibility. Strategic features such as bumping, train stations, and shortcuts require negotiation and mutual support, reinforcing collaborative problem solving and prosocial interaction. In this way, the game's mechanics cultivate teamwork alongside computational reasoning.

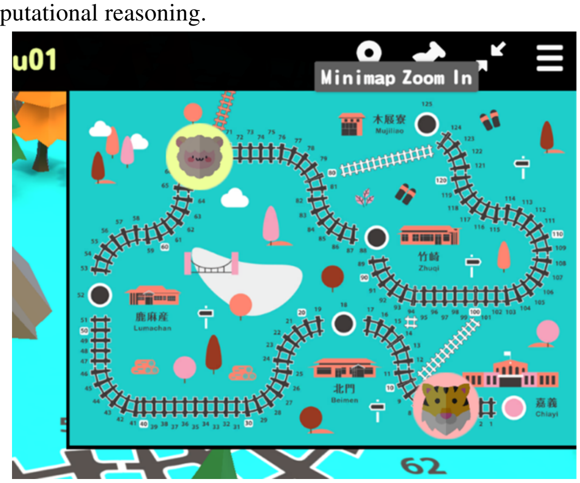

Fig. 8. Mini-map displaying player positions and goal proximity, with the starting point marked in red and the destination point marked in black.

C. Additional Gameplay Features

Special tiles include ladders (a shortcut which transport players to the other end), safety zones (which provide immunity from bumping), and bump triggers (which swap player positions). These mechanics add depth and unpredictability to the game.

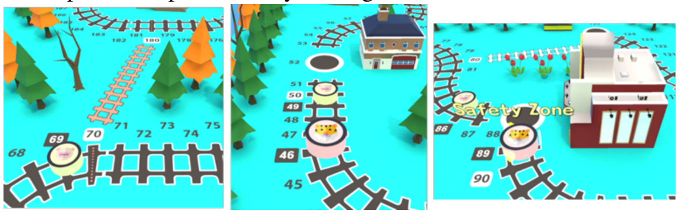

Fig. 9. From left to right: Visual examples of ladder tile, potential bumping scenario, and safety zone tile.

D. Game Achievement: Aquamarine

Players can use earned coins to automate calculations (500 coins per use) or customize a personal aquarium. This sub-game includes marine life with educational descriptions, encouraging ecological awareness, creativity, and personalization.

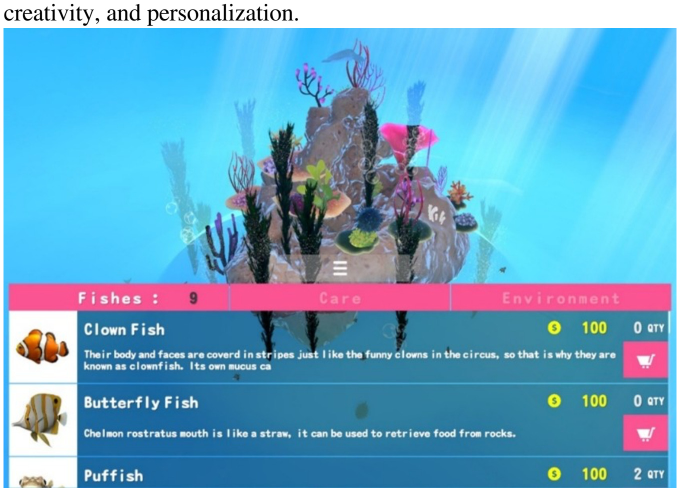

Fig. 10. Marine life purchase screen in the marketplace interface, categorized into Fishes, Care, and Environment sections, allowing players to buy fish, food, and aquatic decorations.

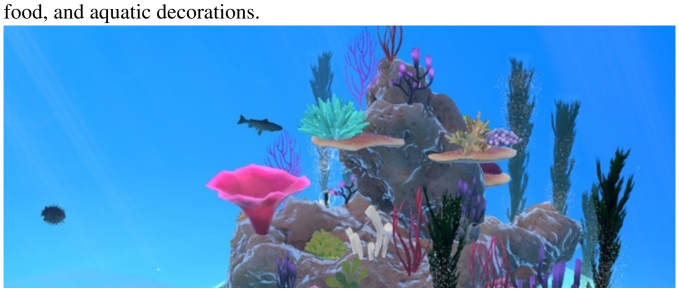

Fig. 11. Aquarium closeup showing a decorated tank with a puffer fish swimming near the bottom.

E. System Architecture and Formative Assessment

The app includes a backend system for user registration and learning analytics. Upon sign-up, users provide demographic data, enabling tracking of gameplay behavior and learning outcomes. ComputUp supports single and multiplayer modes, making it suitable for classroom or small group use. All gameplay activity, including response accuracy, time spent, and in-game decisions, is logged and visualized on a dashboard for educators and researchers. These analytics provide formative feedback opportunities [21], allowing teachers to monitor learners' strategies in real time and adapt their instruction accordingly. Educators can identify which CT elements, such as decomposition or abstraction, pose difficulties, and provide targeted scaffolding accordingly. This data-driven approach transforms gameplay logs into actionable learning insights.

IV. Conclusion

ComputUp provides a dynamic tool for integrating CT and STEM in both individual and collaborative contexts. Its adaptive gameplay, data tracking, and Chance card challenge structure make it suitable for game-based learning and skill development. The aquarium sub-game and creative features further support motivation and promote interdisciplinary engagement. Educators and trainers can leverage backend analytics for formative assessment and personalized instruction. These mechanisms are deliberately designed to foster both strategic reasoning and collaborative decision-making, allowing real-time monitoring of learners' strategies and progress, and offering players opportunities to develop cognitive flexibility and social-emotional skills in a playful, interactive environment. Through gameplay with *ComputUp*, learners are expected to develop domain-specific knowledge and problem-solving skills, and foster prosocial attitudes.

Theoretically, this study verifies that arithmetic-based strategy games can serve as effective carriers for CT cultivation, extending the operational definition of the four CT elements into non-programming contexts. Practically, *ComputUp* offers a reusable, scalable framework that combines arithmetic-driven interaction, interdisciplinary challenges, collaborative mechanics, and data tracking, providing a model for educational game developers.

Future research may empirically evaluate *ComputUp*'s effects on CT development and collaborative behaviors, explore its integration into classroom and remote learning environments, and examine long-term motivational outcomes.

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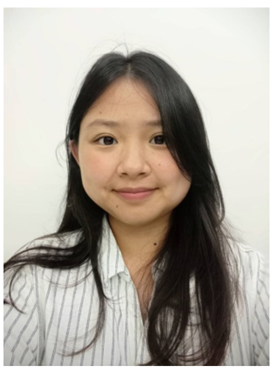

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