Revista Brasileira de Informática na Educação – RBIE
Brazilian Journal of Computers in Education
(ISSN online: 2317-6121; print: 1414-5685)
https://sol.sbc.org.br/journals/index.php/rbie

Submission: 19/08/2025; Camera ready: 02/07/2026; 1st round notif.: 30/05/2026; Edition review: 10/07/2026; New version: 22/06/2026; Available online: 10/07/2026; 2nd round notif.: 23/06/2026; Published: 10/07/2026;

# On the use of a Mechanical Computer Simulator Board-game to Teach Computational Thinking

*Lara Oliveira Esteves*
*Universidade Federal de Juiz de Fora*
*ORCID: 0009-0004-4422-7773*
*lara.esteves@estudante.ufjf.br*

*Lara da Silva Dias*
*Universidade Federal de Juiz de Fora*
*ORCID: 0009-0005-9744-1455*
*lara.dias@estudante.ufjf.br*

*Maria Luísa Riolino Guimarães*
*Universidade Federal de Juiz de Fora*
*ORCID: 0009-0002-7390-0459*
*maria.guimaraes@estudante.ufjf.br*

*Júlia de Paula Campos*
*Universidade Federal de Juiz de Fora*
*ORCID: 0009-0002-3194-412X*
*julia.paula@estudante.ufjf.br*

*Lorenza Moreno*
*Universidade Federal de Juiz de Fora*
*ORCID: 0000-0001-5335-6252*
*lorenza.moreno@ufjf.br*

*Alessandreia Oliveira*
*Universidade Federal de Juiz de Fora*
*ORCID: 0000-0002-7169-587X*
*alessandreia.oliveira@ufjf.br*

*Bárbara M Quintela*
*PPGMC Universidade Federal de Juiz de Fora*
*ORCID: 0000-0002-5320-4109*
*barbara.quintela@ufjf.br*

## Abstract

*Computational Thinking (CT) fosters the development of essential competencies, including problem-solving, analytical thinking, continuous learning, collaboration, adaptability, and flexibility. These skills equip individuals to address the challenges of the contemporary world. Unplugged activities have gained recognition as a viable and effective approach, particularly in the context of Brazilian education, where introducing computing in primary schools faces challenges such as limited teaching materials and technological resources. This study presents the use of a marble-powered mechanical computer simulator board game to teach fundamental CT concepts in 40-minute workshops. The workshops were conducted with ten distinct mixed groups of students aged 10 to 18 during visits to the Science Center at the Federal University of Juiz de Fora between October 2024 and June 2025. Due to the limited availability of the original game board, we developed a strategy to accommodate larger groups. Students were organized into groups of four, each receiving a laminated A3 paperboard replica of the original game. After the challenges were explained, students initially drew their solutions on the paperboard, exercising their abstraction and decomposition skills. Subsequently, each group tested its algorithm by placing components on the original board to verify its correctness. In addition to the workshop, participants were asked preliminary questions to assess their prior knowledge of Computer Science-related undergraduate courses and their interest in pursuing a university degree. Results indicate gender disparities in higher education interest between public and private school students. Among public school participants, 30.71% of female students expressed interest, compared to 22.45% of male students. In contrast, private school groups showed a smaller gender gap (22.45% female and 21.77% male). When questioned specifically about pursuing STEM careers, most students were unfamiliar with the term. Notably, the gender gap was more pronounced in private schools, where 10.88% of male students expressed interest, compared to only 3.4% of female students. Meanwhile, in public schools, 7.48% of female and 5.44% of male students indicated interest in STEM careers. These findings highlight the potential of unplugged activities to democratize CT education while underscoring the need for targeted interventions to address gender disparities and STEM awareness in both public and private school settings.*

***Keywords:*** *Computational Thinking; Teaching Computer Science; Unplugged; Serious Game.*

*Cite as: Esteves, L. O., Dias, L. S., Guimarães, M. L. R., Campos, J. P., Moreno, L., Oliveira, A., & Quintela, B. M. (2026). On the use of a Mechanical Computer Simulator Board-game to Teach Computational Thinking. Revista Brasileira de Informática na Educação, vol. 34, pp. 1049–1069. https://doi.org/10.5753/rbie.2026.6371.*

# 1 Introduction

In 2022, the Brazilian Ministry of Education (MEC) approved a complement to the Common National Curriculum Base (*Base Nacional Comum Curricular* - BNCC), detailing how digital skills should be introduced as a curricular component in primary and secondary education [Cruz et al., 2023]. The Computer Science component encompasses three main axes: Computational Thinking, Digital World, and Digital Culture [Guarda and Silveira, 2023].

Several approaches have already been proposed for teaching Computational Thinking and programming [Pontes et al., 2019]. More recently, some of the approaches that have been explored include plugged strategies, such as educational games [Silva et al., 2024], robotics integration [Feitoza and Cunha, 2024], purely unplugged activities [Araujo et al., 2024], or even hybrid approaches combining plugged and unplugged methods [Berto et al., 2019].

Among the main challenges faced in implementing this component in primary and secondary education are the lack of financial resources, teacher training, varying school realities, inadequate technological infrastructure, and insufficient pedagogical strategies, among others [Braz and Barcellos, 2024]. Given the limited access to Internet connectivity and technological devices faced by many schools, along with the lack of prior computational knowledge among teachers and students, unplugged activities represent a practical and accessible alternative for most Brazilian schools [Brackmann, 2017]. Computer Science Unplugged was designed to teach Computational Thinking without relying on digital tools. This method can be implemented in various ways, including cards, board games, storytelling, etc [Battal et al., 2021].

This paper details an unplugged activity conducted with distinct groups of primary and secondary school students as part of a University extension workshop. The workshop uses a combination of storytelling and a marble-powered mechanical computer game, *Turing Tumble*, to teach preliminary concepts of Computational Thinking. Results indicate that the approach was highly engaging for all students and demonstrated a noticeable impact in sparking their interest in STEM courses, despite limitations in time and materials.

Although the use of *Turing Tumble* has been explored in international contexts, its application within the Brazilian educational landscape remains unprecedented. The primary novelty of this work lies in overcoming resource scarcity to democratize access to this educational tool. By presenting a scalable, low-cost methodology using laminated paperboards and a linguistic and cultural translation of the game's narrative into Brazilian Portuguese, this approach allows large groups of students from public schools to interact collaboratively with a single physical game set. This contextualized adaptation bridges the gap between imported educational technologies and the practical reality of Brazilian primary and secondary education.

The paper is structured as follows. Section 2 presents the theoretical background. Section 4 outlines the materials and methods, followed by results and discussion in Section 5, which also includes the limitations and impacts of the presented approach.

## 2 Theoretical Background

Computational Thinking (CT) was popularized by Wing (2006), who posed a series of questions and statements exploring how humans solve problems and the parallels to computer functionality. Over time, more formal definitions of CT were developed and integrated into the field of Computing Education. Grover and Pea (2017) define CT as a structured problem-solving process that encompasses logical reasoning, algorithmic thinking, pattern recognition, abstraction, generalization, evaluation, and automation. This definition was later refined and expanded in an operational matter by Santana et al. (2021), incorporating additional perspectives to better align CT with educational practices.

Computational Thinking is based on four fundamental pillars that guide the process of understanding and solving problems as described in Table 1.

Table 1: Computational Thinking pillars [Santana et al., 2021].

| **Pillar** | **Description** |
|---|---|
| Abstraction | Involves identifying and focusing on the essential elements of a problem while eliminating irrelevant information. This process reduces complexity, enabling the formulation of simpler and more effective solutions; |
| Decomposition | Refers to breaking down complex problems into smaller, more manageable parts, facilitating the analysis and resolution of each component individually; |
| Pattern Recognition | Entails identifying similarities or regularities in problems or processes, allowing the reuse of previously known solutions in new contexts. This practice helps save time and resources; |
| Algorithmic Thinking | Involves designing a set of clear and logical instructions (algorithms) to solve problems in a structured and efficient manner. |

Those pillars enable individuals to apply computational reasoning logically and systematically across various domains, fostering an innovative and efficient approach to problem-solving. Additionally, teaching Computational Thinking (CT) often employs resources that connect students with social issues, encouraging their active engagement in the learning process.

CT promotes the development of competencies such as problem-solving, analytical thinking, continuous learning, collaborative work, adaptability, and flexibility. These skills prepare individuals to face the challenges of the contemporary world, regardless of their professional field [Garcia and Borges, 2023]. Thus, CT is recognized as a transversal competency applicable to diverse fields of knowledge, playing a crucial role in equipping individuals to tackle current challenges with creativity and critical thinking [Lima et al., 2022].

Given the reality of Brazilian education and the challenges associated with introducing computing in primary schools, particularly due to the scarcity of teaching materials and technological resources [Almeida et al., 2021; Cruz et al., 2023], unplugged activities have been increasingly recognized as a viable and effective approach. These activities provide an accessible way to teach fundamental computing concepts without requiring expensive equipment or advanced technological infrastructure. In this context, França and Tedesco (2021) developed a gamebook and compared the teaching of CT using it in a fully unplugged scenario and in a hybrid approach, incorporating resources such as Scratch to implement and test algorithms.

Moreover, recent systematic literature review revealed that approaches incorporating gender and racial considerations are still scarce [Quintela et al., 2024]. This gap indicates that, while the field advances in accessible methodologies such as unplugged activities, the concern with representativeness and social inclusion has not kept up with the same pace. The lack of diverse characters, narratives, and examples in teaching materials can reinforce stereotypes and create barriers to identification for students from under-represented groups.

# 3 Related Works

There is a growing body of initiatives that investigate Computational Thinking (CT) and introduce basic computing concepts through accessible, engaging strategies. Many of these studies leverage unplugged approaches to broaden access, promote inclusion, and sustain engagement, especially in contexts with infrastructure constraints.

Mapping and synthesis works help consolidate evidence and refine terminology. Carvalho and Braga (2022) analyze WAlgProg/CBIE (2015–2019) publications on CT (as popularized by Wing), noting the frequent decontextualized use of the term but a trend toward stronger conceptual grounding and recognition of CT's interdisciplinary problem-solving potential. Complementarily, a broad systematic review and meta-analysis of 49 studies (2006–2022), conducted by Chen et al. (2023), shows substantial positive effects of unplugged activities, especially board/card games, on K–12 CT skills (Hedges's $g = 1.028$, $p < 0.001$), with robustness across grades, class sizes, and intervention duration; the review also highlights that CS/STEM is the dominant context and that CT diagnostics are commonly used assessment tools.

Additionally, Martins, Silva and Neris (2023) present the first systematic mapping focused specifically on CT teaching for preschool children aged 4–5 years. The study synthesizes 82 primary works (2010–2020) that propose, implement, or evaluate tools and activities, both unplugged and plugged, and also considers teacher training initiatives. Results show a growing research interest in recent years, predominance of physical artifacts and unplugged strategies, and limited autonomy of preschool teachers in implementing CT activities (often mediated by computing professionals). The mapping categorizes approaches (e.g., daily routines, storytelling, robotics, ScratchJr), tools/kits (physical, hybrid, virtual), participant profiles, and roles of implementers, revealing that teacher training positively influences engagement and implementation capacity. The authors recommend integrating CT into early childhood curricula and expanding teacher preparation to enable autonomous, sustained practice. Together, these works justify the use of unplugged strategies and motivate clearer operationalizations of CT constructs in empirical studies.

Several interventions adopt playful, low-cost unplugged designs to cultivate core CT practices (abstraction, decomposition, pattern recognition, algorithmic thinking) in early grades. Rosa et al., 2021 presents PC-Câmbio, an unplugged activity based on exchange mechanisms that targets logical reasoning, abstraction, and pattern recognition in arithmetic/algebraic tasks for 4th graders, evaluated via pre/post-tests and classroom observations with 26 students; the results indicate the potential to strengthen foundational learning aligned with contemporary technological demands.

In a similar spirit of making algorithms tangible for novices, Ferreira et al. (2025) enacts bubble sort through a cup game and a choreography activity with 24 1st-grade students over two sessions (7h total), evidencing decomposition (pairwise comparisons), abstraction (focus on compare/swap), and pattern recognition (iterations until stopping condition), while also discussing practical limitations and instructional design extensions (e.g., cultural elements to reinforce engagement).

Expanding unplugged repertoires beyond algorithms, Hsu and Rodrigues (2025) structure workshops with Tangram and origami, integrating STEAM for 5th graders and emphasizing connections with BNCC (lists, graphs, algorithms with selection, decomposition), with reports of conceptual understanding, everyday contextualization, and meaningful learning. Additionally, Araujo and França (2025) report a hybrid intervention combining unplugged activities with block-based programming (Blockly) for 151 fifth-grade students in three hands-on lessons focused on CT pillars. The study observed high engagement during unplugged tasks, but notable struggles with advanced Blockly concepts such as conditionals, underscoring the effectiveness of hybrid modalities while highlighting the need for extended practice with foundational programming constructs before introducing complex topics.

With a focus on early childhood, Yang et al. (2023) conduct a multi-group quasi-experiment (N=108) in which story-inspired programming (using robots or tablets) outperforms unplugged activities in CT gains for 5-year-old children. The study demonstrates storytelling as a culturally responsive pedagogy that sustains engagement and promotes inclusion regardless of gender or socioeconomic background, an important finding when weighing choices between strictly unplugged experiences and hybrid/plugged solutions in early childhood education.

Physical manipulatives and robot-mediated experiences can catalyze motivation and provide concrete referents for algorithmic behavior. Kunovic and Krzic (2021) present an internet-controlled educational robot (Fischertechnik, Arduino Uno) and a "marble computer game", explored in workshops with students aged 9–14 who programmed basic functions. The study compares motivation across physical, digital, and robotic versions of the marble game, offering practical insights for sustaining programming motivation and, by extension, CT learning.

While unplugged interventions gain attention for their cost-effectiveness and accessibility, there are also digital proposals focused on foundational domains. Katoningsih and Mahadewi (2023) investigate the Marble Game application to support number recognition, counting, and writing in kindergarten groups (A and B), addressing pandemic-related learning gaps through observation, interviews, and classroom practice. Findings indicate effectiveness and age appropriateness, showing that even without computers at every stage, simple digital artifacts can support the development of preconditions for CT.

Card games also appear as tools for teaching and assessing computing concepts. Mourão et al. (2025) introduce *Cartas de Classe*, a card game for teaching and assessing OOP in higher education, with two card levels: (Level 1) UML-inspired structures for basic concepts (classes, attributes, methods, objects) and (Level 2) Java and IDE elements for advanced topics. In a study with 16 students (group and individual formats), the protocol mobilizes CT strategies (e.g., pattern recognition and logical sequencing) to build complete and correct classes, reporting engagement and viability as a learning instrument aligned with BNCC.

Beyond early grades, there are investigations that explore the age-transversal dimension of CT practices. Nunes and França (2025) present unplugged workshops aligned with CT pillars and BNCC competencies (e.g., EF01CO01–EF05CO04), conducted with 6th graders and elderly participants in different school and cultural contexts. Activities include Crazy Recipe (step ordering and debugging), Pattern Detective with Color Rulers (recognition and prediction), and body-based algorithmic dynamics. The study highlights how concrete mediation, accessible language, and manipulable materials stabilize computing concepts across diverse cognitive profiles, maintaining principles of inclusion and computational literacy throughout life.

In the international context, the original studies and applications of *Turing Tumble* have been explored as a bridge between abstract computational architecture and tangible cognitive models [Boswell and Boswell, 2017]. Research indicates that the game's mechanical interface reduces the cognitive load typically associated with learning programming syntax, framing computation through physical manipulation and material logic.

This intermediate category can be better understood through the lens of "tectonic computation", a paradigm proposed by Papanikolaou (2026). In this approach, computation is not a symbolic abstraction but a physical phenomenon where information is encoded directly into form, geometry, and material interactions. The *Turing Tumble* board acts as a gravity-driven state machine, making logical operations tangible and visible through continuous kinetic movement. Consequently, this hands-on materialization allows students to experience self-guided debugging, increasing their autonomy and spatial understanding of data flow without relying on digital screens while interacting with a system that is theoretically proven to be Turing-complete [Pitt, 2023].

While only unplugged approaches—such as paper-and-pencil tasks, card games, or role-playing physical activities—are highly accessible and effective for introducing fundamental CT pillars, they often rely on the external validation of a teacher or peer to identify logical errors. In pure unplugged scenarios, the state of the system is held entirely in the participants' minds, which can limit independent error correction. In contrast, integrating a mechanical simulator like Turing Tumble situates the activity in an intermediate category. It maintains the independence from digital infrastructure (screens, internet, or electricity) characteristic of unplugged methods, while successfully incorporating the autonomous systemic feedback typical of plugged approaches. This tangible materialization of algorithms allows students to observe data flow and failures in conditional logic in real time, significantly enriching the debugging experience, which is often too abstract in unplugged dynamics.

In summary, the literature indicates that diverse unplugged and interdisciplinary strategies, whether playful, narrative, embodied, or game-based, have proven effective in introducing CT within Basic Education. The study reported here contributes to this body of work by employing the Turing Tumble as an outreach resource, combining practical experimentation with playfulness to stimulate Elementary and High School students' interest in Computing.

# 4 Materials and Methods

The proposed workshop was initially developed in the context of an outreach project called *Meninas Digitais UFJF*, in order to bring CT concepts to middle school girls in a playful way. The project is supported by the national program *Meninas Digitais* (Digital Girls, in English) from the Brazilian Computer Society.

The choice of a board game that simulates a mechanical computer with colorful parts and a female main character who is a space engineer proved to be successful when applied to an initial small group of 6 girls [Guimarães et al., 2023]. However, as we had the demand to offer the activity to larger groups, we proposed a new approach that was initially applied to two groups of high school students during the National Science and Technology Week, described in the conference paper Quintela et al., 2025.

In this paper, we detail the approach and present novel results from the application of the same workshop to 9 mixed groups of middle school students from both public and private schools. The methods are described in the following subsections.

## 4.1 Fundamental CT Abilities

Initially, the official complement for CS in the Brazilian National Common Curricular Base (BNCC) was analyzed [Brasil, 2022], and the main abilities that are common to both primary and secondary school students were identified and grouped to be considered while proposing the activity, all belonging to the Computing curricular component, which is officially identified by the acronym **'CO'** within each skill's code (e.g.,EF05**CO**03). The abilities that are considered within this work are described in Table 2.

Table 2: Fundamental CT abilities for primary and secondary school students..

| **Ability** | **Description** |
|---|---|
| Computational Logic (EF05CO03) | Perform operations of negation, conjunction, and disjunction on logical statements. |
| Algorithms with Conditional Selection (EF05CO04) | Create and simulate algorithms represented in oral, written, or pictorial language that include sequences, repetitions, and conditional selections to solve problems independently and collaboratively. |
| Algorithms (EF15CO02) | Build and simulate algorithms, independently or collaboratively, that solve simple and everyday problems using sequences, conditional selections, and instruction repetitions. |
| Decomposition (EF15CO04/ EM13CO01) | Apply the decomposition strategy to solve complex problems by breaking them into smaller parts, solving them, and combining their solutions. |
| Abstraction (EM13CO02) | Explore and construct problem solutions through refinements, utilizing various levels of abstraction from specification to implementation. |

### 4.2 The Board-Game and its parts

*Turing Tumble* is an educational game that simulates a mechanical computer with several components, the main one being a two-dimensional board that has its structures and mechanisms fixed for support [Pitt, 2023]. The main parts are indicated in Figure 1: there are two triggers with ball releasers positioned on their upper part (1) that are used to launch a new ball, and two levers at the bottom of the board (2), known as the computer start.

When the start button on one of the bottom levers is pressed, its respective trigger releases a ball. Then, when a ball reaches the bottom of the board, another one from the same side of the lever is released through a mechanical connection behind the board. The mentioned balls can be blue or red, and they must be inserted into their respective ball releasers. The balls perform a mechanical logic while interacting with the board parts, and the execution is continuous until there are no balls available.

The manageable parts of the game, their representation or functions, their respective numbers in Figure 1 and their relationship to computational concepts are presented in Table 3.

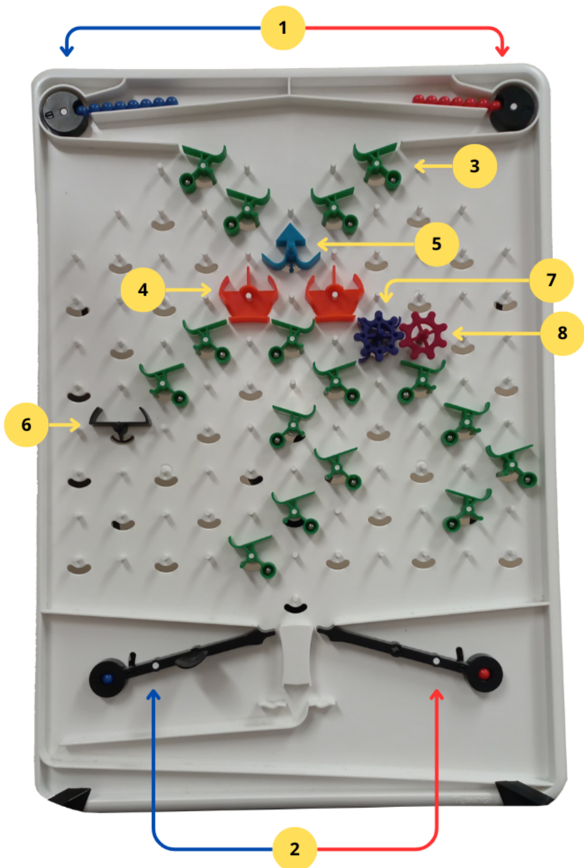


Figure 1: Turing Tumble board and parts. Adapted from Story, 2024.

Turing Tumble includes a comic book that ties the challenges to the narrative of Alia, a space engineer who seeks rescue on a distant planet. Each challenge provides detailed instructions, including the number of balls required for input and output, the initial configuration of the board

Table 3: Relationship between the manageable parts, their representation or functions and their relationship to computational concepts.

| # | Parts | Representation/Function | Computational Concepts |
|---|---|---|---|
| 1 | Ball releaser | Release one ball at a time | Data input |
| 2 | Lever | When pressed activates the ball releaser | Simulation start/continue |
| 3 | Ramps | Carries the ball and determines it is direction | Conditional flow |
| 4 | Crossovers | Reverses the direction of the balls like a cruiser | Data bus |
| 5 | Bits | Represents a memory of one bit according to it is direction and reverses the current state as well Crossovers | Logic gate NOT (inverter) and operation binary |
| 6 | Interceptors | Interrupts the path of the ball and then ends the execution by storing the information | Random Access Memory (RAM) and registers |
| 7 | Gear-Bits | Record how many times an event has occurred | Count registers and increment/decrement operations |
| 8 | Gears | Transfers the movement | Sequential logic and chained processing steps |

(pre-placed components), and the parts available to solve the puzzle. As Alia's story unfolds, the complexity of the challenges increases, introducing new components and mechanics to the game.

With an age restriction from eight years old, the game allows either playing alone or in small groups. A PDF guide and videos for educators who want to develop the computational concepts using Turing Tumble are available at the developer website [Story, 2024]. For those who have access to a 3D printer, the developers also offer the files for printing the parts so that those who purchase the game are able to recreate copies of the parts if necessary. An online simulator with the challenges is also available, which allows for both planning beforehand the challenges, and also practicing remotely and even in online rooms with other participants [Twilton, 2022]. The latter is not explored within this work, but this information is shared among the participants at the end of the workshops, so that they can continue solving the challenges in case they have access to a computer with an internet connection.

Materials used in this workshop include one copy of the Turing Tumble Game (Figure 2), six A3 laminated paper copies of an art inspired by the board (Figure 3) developed within this project by the authors, felt-tip pens, and a TV screen to present the comic book and the challenges, which were adapted in the format of a slideshow and translated to Portuguese by the members of the project (Figure 4). Both paperboard and the slides are available for download at the extensionist project website [1].

## 4.3 Infrastructure

The Federal University of Juiz de Fora operates a Science Center that hosts school groups from the municipality and neighbouring regions. During the visitation booking process, each school

[1] https://www2.ufjf.br/meninasdigitaisufjf/oficinas/oficina-turingtumble/

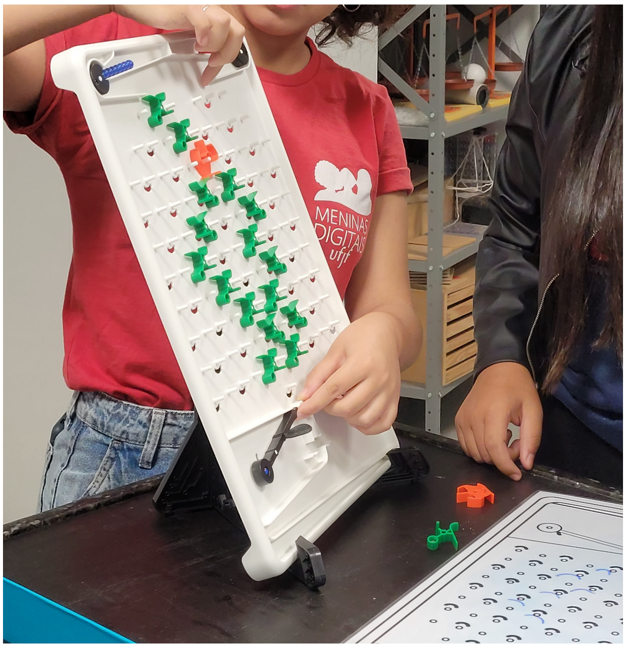


Figure 2: Simulation using the board.

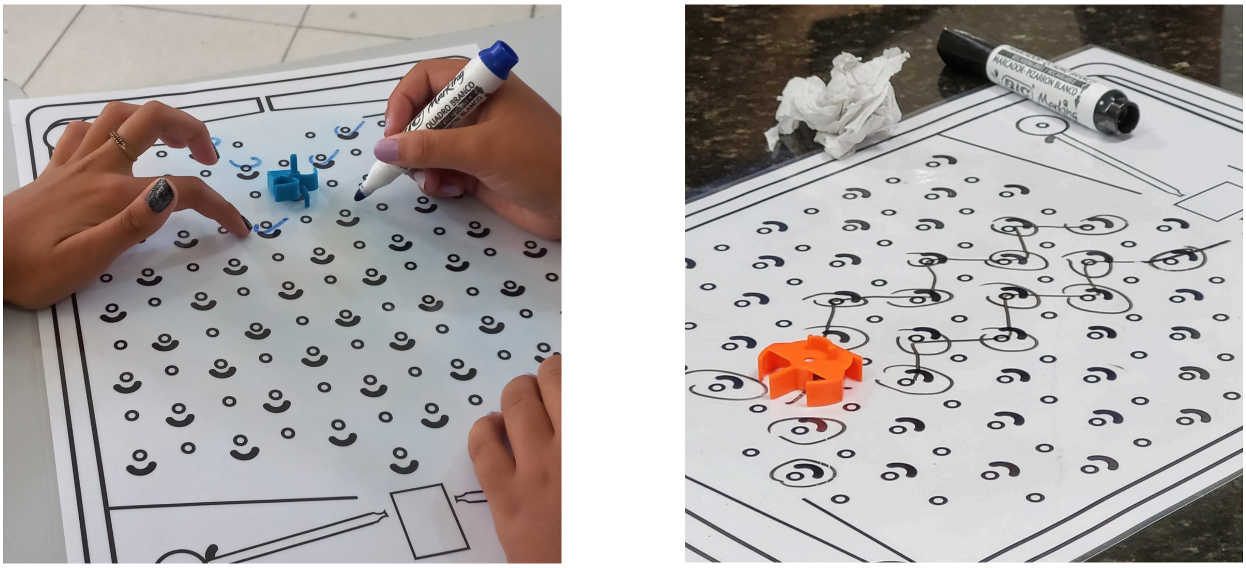

Figure 3: Paperboard used for drawing the solutions before testing on the marble-powered board.

selects activities from a provided list for their students to participate in. The workshop described in this study was initially offered during the National Week of Science and Technology in October 2024, and in 2025 it was incorporated as the inaugural Computer Science department initiative at the Science Center.

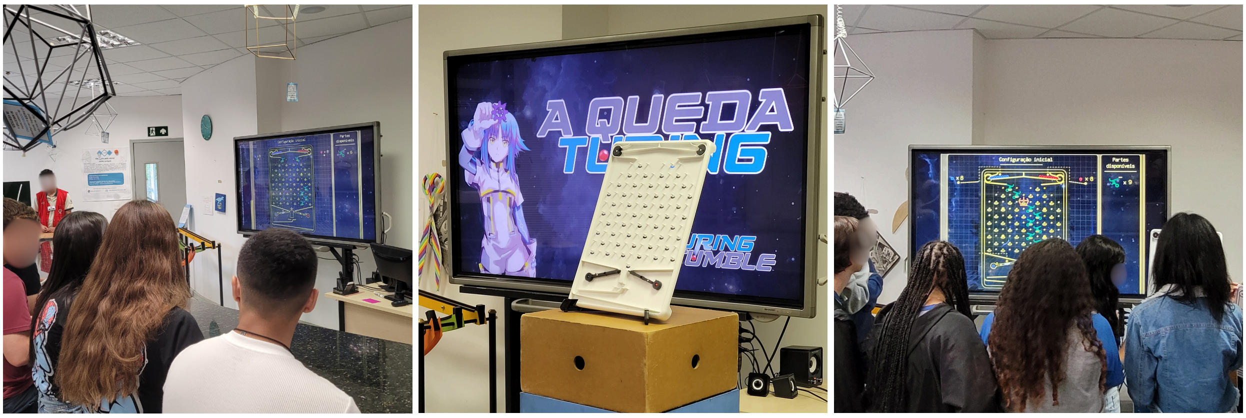


Figure 4: Presentation of the slides with the story and description of the challenges using a TV.

## 4.4 Methods

The workshop presents a student-centered, game-based, and hands-on learning approach. Basically, the facilitators present challenges and the participants are invited to collaboratively explore possible solutions and test them. Each step taken during the application is explained in this section.

Upon receiving the participants, a relaxed conversation (icebreaker) was held to create an inclusive atmosphere and understand the context the students live in and their knowledge, present the initiative and start the activity. Some questions related to the students' previous knowledge of the University and main differences between technology courses were asked, and quantitative responses were grouped by gender and are presented in Section 5.

To introduce the game's core mechanics, a scaffolding strategy was used. Initially, the board and the first components, which were the ramps (number 3 in Figure 1) were presented to the students. We began with the first exercise proposed by the guidebook that comes with the game. At this point, the problem was presented partially solved, with some ramps already positioned on the board. This partially solved set-up was designed to lower the initial cognitive load and build the students' confidence. Then, we displayed the challenge in a slideshow format so that all students could view the task in a larger image: to make only the blue balls fall. The image showed the board with some of the ramps in place and the number of remaining parts available to complete the challenge.

Since it was the first example and aimed at helping students understand how the board works, the exercise was designed as a collective, guided practice. We encouraged the students to suggest possible solutions so they could begin to internalize the logic behind the activity. Participants were invited to "think-aloud" by verbalizing where they thought the pieces should be placed, ensuring that everyone could follow the group's reasoning. Then, one of the volunteers implemented the group's suggestion by placing the missing parts on the board and pressing the start button, providing immediate feedback on whether the challenge was successfully solved.

After completing the first example, we presented a new challenge with a similar structure, designed to increase student autonomy. The board already had some parts positioned, and the students were informed of the constraints, such as which and how many additional parts could be used to complete the task. In this second challenge, for example, only six ramps could be used.

The students, organized into small groups, were then invited to prototype their proposed solutions by drawing them on laminated sheets using felt-tip pens, marking where they believed the parts should be placed to achieve the expected result.

This moment was important to exercise abstraction, as the act of drawing required the students to develop the ability to mentally visualize and model the path the balls would need to follow to reach the desired final configuration. This intermediate step of creating a static representation of their algorithm forced them to predict the final configuration without immediate physical execution, strengthening their planning and problem-solving skills.

While the groups worked on their solutions, the volunteers walked around the room, answering questions and offering guidance when necessary. From this point on, for the remaining challenges, each group was invited one at a time to interact with the physical board. Each student was encouraged to participate by either placing one of the missing pieces or pressing the start button to test their solution. After the execution, all students were invited to discuss the result and, if applicable, propose corrections or alternative solutions, fostering a collaborative and idea-sharing environment.

The second part (crossover) is introduced after the groups can solve at least two challenges with the ramps. Taking into account that the number of challenges that can be presented depends on the resolution time of each class, four challenges were solved involving the two presented parts, which were the ramps and the crossovers. The difficulty levels gradually increased, and the parts were presented connected to the story as the character Alia faces new challenges.

There are three main moments in the resolution of the challenges. Firstly, the description of the challenge by the members of the project, showing the initial configuration on the board and the parts that can be used, followed by the delivery of the materials, a laminated paper board for each group, felt-tip pens for each one and a part for familiarization (Figure 4). Secondly, each group develops a solution on its laminated paper board knowing that there are multiple possible solutions (Figure 3). Lastly, as soon as all the groups outline their solutions, the first group that finishes is invited to implement their solution on the board so that every group can solve at least one challenge on the board. If the solution does not reach the expected result, other participants are invited to collaborate (Figure 2).

Throughout the process, the participants work with concepts related to the pillars of computational thinking, such as abstraction when using the laminated paper board before testing on the real board, algorithms when deciding the placement of the parts, and decomposition when thinking of each step of the solution to solve problems efficiently with creativity and critical and strategic thinking. At the end, the students are asked if they liked the experience and if their considerations about computing have changed.

Qualitative insights regarding student engagement were gathered through structured observational notes taken by the facilitators during the workshops. Facilitators recorded instances of collaborative problem-solving, verbalized breakthroughs (think-aloud moments), and informal post-activity feedback. As this study reports on an educational intervention conducted within the scope of a university extension project, data collection was restricted to these observational notes and anonymous, aggregated responses to general interest questions. Ethical guidelines regarding the privacy and anonymity of the minors were maintained throughout the process.

# 5 Results

The activities were initially conducted with two groups of high school students during the National Science and Technology week. Afterwards, the workshop was incorporated into the Science Center activities program and applied to eight groups of middle school students. The results are presented separately by education level and later consolidated for discussion.

## 5.1 High School Students

Two groups (C1 and C2) from the same school from Juiz de Fora-MG attended the workshop on the same day in October 2024. C1 consisted of 16 students (9 boys and 7 girls), while C2 consisted of 21 students (12 boys and 9 girls). In both classes, the participants were instructed to organize themselves into groups of up to four people, resulting in the distribution shown in Table 4.

Table 4: Quantitative of groups by gender and classroom..

| Classes/Groups | Girls only | Boys only | Mixed |
|---|---|---|---|
| C1 | 1 | 2 | 3 |
| C2 | 2 | 1 | 2 |

Initially, no significant differences were observed in the performance of the groups in any of the classes, except regarding their confidence in their own abilities. In C1, the all-girls group pointed out, before attempting the first challenge, that the activity was complex and difficult to carry out. However, like the other groups, they successfully completed all the challenges without showing difficulty.

A few questions were asked to the students at the beginning of the workshop to assess their previous knowledge. The questions were designed to be quantitative in nature, closed and dichotomous, where the students had two options: raise their hand for a positive answer and keep them down for a negative one. The positive answers, grouped by gender, are shown in Table 5.

Table 5: Quantitative of students answers grouped by gender and classroom. *Initially 2 but at the end of the activity one of the participants changed her answer to the question.

| | Female | | Male | |
|---|---|---|---|---|
| **Questions** | **C1** | **C2** | **C1** | **C2** |
| **[Q1]** Have you been to the University before? | 5 | 7 | 7 | 5 |
| **[Q2]** Do you intend to attend an undergraduate course? | 6 | 9 | 8 | 5 |
| **[Q3]** Do you want to pursue a course in STEM? | 1 | 3* | 0 | 2 |
| **[Q4]** Do you know the differences among the technology courses? | 0 | 0 | 0 | 0 |
| **[Q5]** Do you know what Computational Thinking means? | 0 | 0 | 0 | 0 |

The questions were ordered to provide relevant information about the context and introduction of the activity, and the decrease in positive answers demonstrates the limitations of contact in relation to the STEM area. The activity aroused curiosity and even interest on the part of the students, whose comments could be heard throughout the workshop application, exposing the desire to start a degree in the areas of STEM. A C2 girl student reported, at the end of the activity, that she had changed her mind and now considers attending an undergraduate computing course. The authors believe that the positive learning experience provided by the use of the marble-powered computer game, as well as the fact that the workshop was provided by women, might have contributed to this participant manifesting this change in her initial response.

### 5.2 Middle School Students

The same methods were applied to the eight groups of mixed middle school students described in Table 6. Four groups were from public schools, and four groups from private schools, with two from the same school in Juiz de Fora-MG and the other from a school in a neighboring city. In general, the middle school students were more timid at first, but all the students engaged in the activity. In groups C3 and C4 it was observed that the girls-only groups were the first to finish the challenges.

Table 6: Detailed demographic and academic profile of participant groups.

| | | | | Number of Students | | |
|---|---|---|---|---|---|---|
| **Group** | **Type of School** | **School Level** | **Age Group (years)** | **Girls** | **Boys** | **Total** |
| **C3** | Public (Juiz de Fora-MG) | Middle School | 10 | 6 | 10 | 16 |
| **C4** | | | 10 | 10 | 8 | 18 |
| **C5** | Public (Juiz de Fora-MG) | Middle School | 13 | 11 | 9 | 20 |
| **C6** | | | 13 | 10 | 9 | 19 |
| **C7** | Private (neighbor city) | Middle School | 10-11 | 11 | 15 | 26 |
| **C8** | | | 10-11 | 11 | 12 | 23 |
| **C9** | Private (Juiz de Fora-MG) | Middle School | 13 | 8 | 4 | 12 |
| **C10** | | | 13 | 3 | 10 | 13 |

Considering only the schools from Juiz de Fora, half of the students (50.68%) from the public schools (groups C3, C4, C5, and C6) had visited the campus before (Figure 5). Whereas, 72% of the students within the groups from the private school (C9-C10) have answered that they have already been to the University. We weren't expecting affirmative answers from the groups from another city; however, one student has reported that he had already visited the campus.

In public school groups (C3-C6) the female students are the majority in interest in pursuing higher education, 30.61%, while the male students represented 22.45%. Meanwhile, in private schools that difference is not observed, and the relation is inverse, the female students are 21.77% and male students 22.45%. Among those interested in pursuing higher education, when we observe the data stratified by gender, there's an expressive difference (Figure 6). Male students represent 41.5% of the students that intend to pursue higher education and are interested in STEM whereas the female students make 19.4%. The interest in STEM was also more evident in private schools.

Moreover, when we consider the percentage of the students that answered **[Q3]** in relation to the total of students for each group of public or private schools, we observe opposing relations (Figure 7). In public school groups (C1-C6) the number of female students surpassed the number of male students interested in pursuing STEM related courses. Whereas, among the private school groups (C7-C10) the percentage of male students was 3 times higher than the female students.

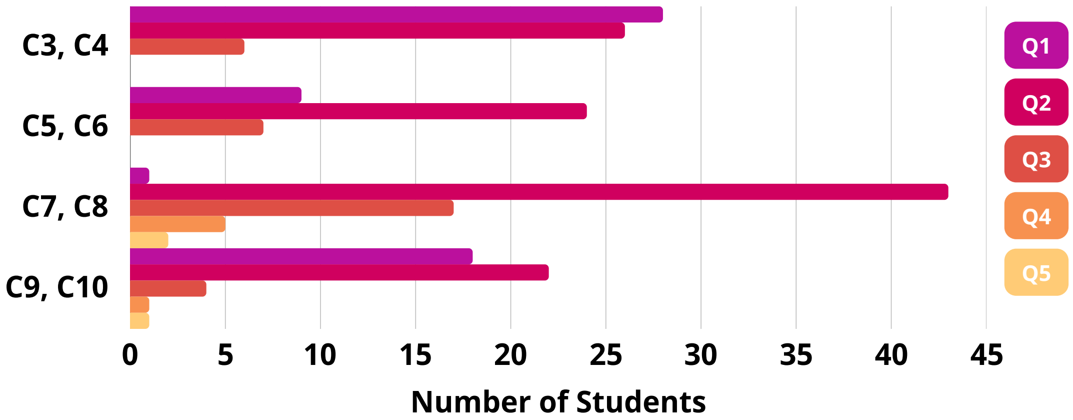


Figure 5: Breakdown of students' responses by school and gender regarding the questions in Table 5.

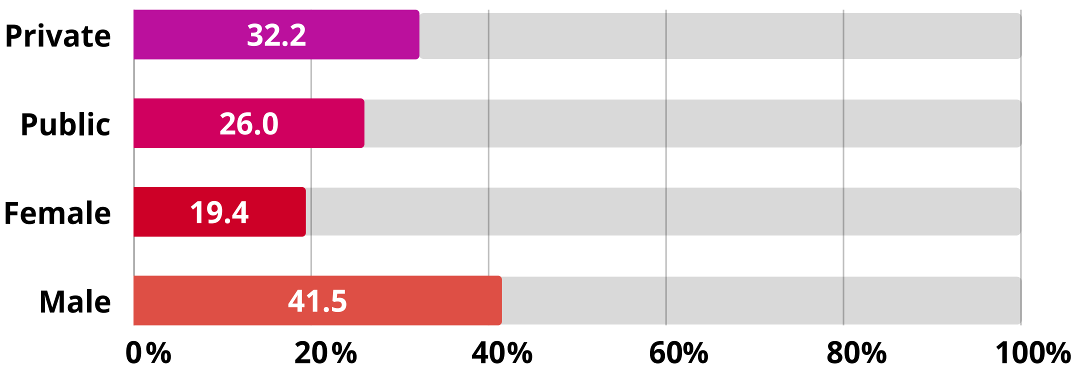


Figure 6: Percentage of students interested in STEM courses among those intending to pursue higher education.

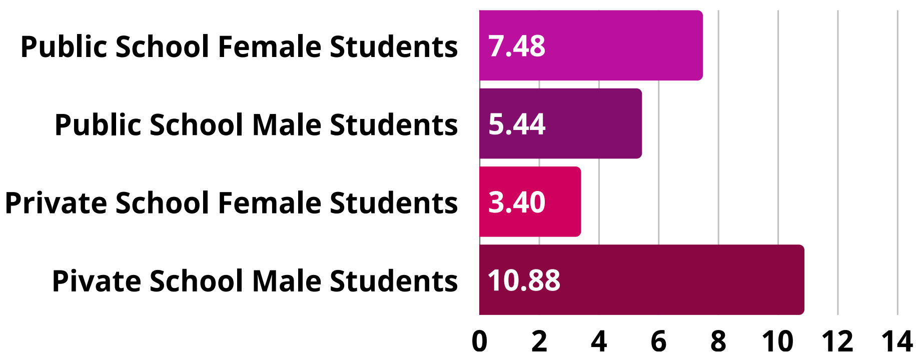


Figure 7: Percentage of students interested in STEM per gender and school type..

Only three female students and three male students from distinct groups of private schools (C7, C8, C9 and C10) reported knowing the difference among CS courses, representing 4% of the students from those groups. Moreover, only three male students from private schools reported having heard the term Computational Thinking before. Among the public school groups, none of the students have responded to questions **Q4** and **Q5** affirmatively.

### 5.3 Limitations

One of the main limitations is the lack of a board for each group of students. Since it is a hands-on activity, the absence of individual boards created a logistical bottleneck, as students had to share the available space and materials. The laminated A3 was developed and proposed as a mitigation strategy to address this problem, allowing groups to work in parallel on the design and prototyping of their solutions.

Furthermore, some groups progressed through the tasks more quickly than others. This resulted in situations where students who finished the activity earlier had to wait for other groups, which could lead to disinterest or loss of focus. To avoid unnecessary waiting, it would be helpful to plan complementary activities or extra challenges for students who finish quickly, such as finding a more optimal solution with fewer pieces or solving a more advanced problem, thus keeping everyone engaged throughout the session.

A potential limitation is the difficulty in addressing the diversity of learning paces among students. While most understood the concepts and solved the challenges, some students may have felt pressured or frustrated, especially those with more difficulties. The lack of individualized support and the fast pace of the activity might have hindered these students' learning, highlighting the importance of adapting the activity to different student profiles.

Another limitation concerns the short duration of the sessions, restricted to 40 minutes and synchronized to other STEM activities for each school visit. The limited time frame only allows a brief introduction to some computational concepts and prevents the resolution of complex challenges. Nevertheless, the sessions promote student engagement and learning, as discussed in the next section.

### 5.4 Positive Aspects and Educational Impact

The structure of the game, with its scaffolded progression of increasing difficulty and the introduction of new components, gradually creates a dynamic environment for student engagement. As it is an open-ended game with unlimited possibilities, the creativity flows and, during the activity, several proposals for new challenges and solutions emerge in a relaxed and enthusiastic way, reinforcing the learning of the concepts. This emergent behaviour strongly affirms that they have not only learned the core concepts but have achieved a level of understanding that allows them to innovate within the game's system. The positive reinforcement from obtaining a correct result is crucial for building self-esteem and self-confidence. This emotional impact is particularly significant for high school students, a group that often faces insecurity and anxiety related to career path decisions while dealing with family, social and economic pressures. By providing tangible moments of accomplishment in a STEM-related activity, the workshop helps build a sense of agency and confidence in their own problem-solving abilities.

The positive emotional impact observed during the workshop can be attributed to the multisensory nature of the Turing Tumble. Recent research in educational psychology demonstrates that learning models integrating visual and tactile stimuli significantly reduce learning anxiety and cognitive barriers, as physical manipulation provides concrete and immediate feedback [Zhan and Cheng, 2025]. In the context of our intervention, this tangible experience transforms an abstract and often intimidating subject into an approachable challenge. Consequently, mitigating this anxiety impelled the students' self-confidence, particularly among the girls. As evidenced by Zhan and Cheng (2025), multisensory learning environments not only alleviate psychological pressure but also substantially enhance female learners' emotional states and motivation. This theoretical foundation aligns with the increased interest in STEM careers expressed by the female participants after interacting with the mechanical board, proving that tangible, hands-on approaches are powerful tools to break psychological barriers in computing education.

Moreover, the activity was intentionally facilitated by female undergraduate and graduate students and a female professor, providing visible and relatable role models and contributing to gender representation. Therefore, the impact extends beyond the acquired Computational Thinking knowledge, also actively working to dismantle gender stereotypes by shaping students' perceptions of who can and should pursue a career in technology.

## 6 Conclusion

This work presented an innovative unplugged activity based on the Turing Tumble game, a marble-powered educational board game that simulates a mechanical computer, to teach and demystify foundational Computational Thinking (CT) concepts to elementary and high school students. The approach, grounded in playful, narrative, and hands-on learning, proved capable of integrating computational logic, algorithm design, abstraction, and problem decomposition in an accessible, interactive, and engaging way. Specifically, the game materializes abstract concepts such as algorithmic flow and conditionals (the path of the marbles) into observable, physical processes, thus lowering the cognitive barrier to entry, even in contexts with limited technological infrastructure.

The implementation of the workshop across different student groups revealed not only the technical and pedagogical feasibility of using Turing Tumble, but also its strong engagement potential. Results showed that, even without prior experience or familiarity with computing concepts, participants were able to solve increasingly complex challenges, demonstrating progress in logical reasoning and problem-solving strategies. Furthermore, the experience had a positive impact on students' perceptions of STEM careers, particularly among female students. This suggests a notable increase in self-efficacy and vocational interest, reinforcing the role of initiatives with female representation in breaking gender stereotypes in the field.

Despite limitations related to the short session time, the lack of multiple game sets, and the diversity of learning paces, the strategy proved adaptable through the use of printed A3 boards, which functioned as low-fidelity prototypes and tools for thought externalization, enabling larger groups to actively engage in planning and simulating solutions. These constraints also indicate avenues for improvement, such as designing differentiated instruction paths with complementary activities for early finishers and developing extended workshop formats to deepen content exploration.

From an educational perspective, Turing Tumble proved to be not only a tool for introducing computing concepts but also a catalyst for creativity, collaboration, and student confidence. The incremental challenge structure, combined with the game's narrative, fostered a dynamic learning environment that promoted a growth mindset, in which mistakes were reframed as opportunities for reflection and solution refinement. This process transforms debugging from a frustrating chore into an engaging puzzle, empowering students to see challenges not as barriers, but as solvable problems.

In conclusion, the use of tangible, game-based resources such as Turing Tumble is an effective alternative for promoting Computational Thinking in basic education, particularly in schools facing restricted access to computers and the internet. By providing meaningful and inclusive learning experiences, this proposal contributes to expanding teachers' methodological repertoire, strengthening students' interest in technological fields, and supporting the implementation of the Computer Science complement to the BNCC, ultimately fostering the development of critical and creative problem-solvers for the 21st century. Future studies could explore extending the workshop to other educational contexts, integrating hybrid (physical and digital) resources, conducting longitudinal assessments of its impact, and performing qualitative analyses of student discourse to better understand their reasoning processes during collaboration.

## Acknowledgements

The authors thank UFJF and its Science Center for the infrastructure provided, as well as the funding agencies CAPES, CNPq, and FAPEMIG. They also extend their gratitude to Professor Igor Knop for introducing Turing Tumble to one of the co-authors (BMQ), which served as the project's initial inspiration.

## References

Almeida, J., Conceição, D., Ferreira, A., Rios, E., Santana, C., & Durães, G. (2021). Sobre a necessidade de recursos educacionais para o ensino do pensamento computacional na educação básica brasileira: Discussão e concepção de repositório educacional do pensamento computacional. *Anais Estendidos do I Simpósio Brasileiro de Educação em Computação*, 39–40. https://doi.org/10.5753/educomp_estendido.2021.14865 [GS Search].

Araujo, F., & França, J. (2025). Pensamento computacional na prática: Uma experiência com blockly e atividades desplugadas no 5º ano do ensino fundamental. *Anais do XXXIII Workshop sobre Educação em Computação*, 918–926. https://doi.org/10.5753/wei.2025.8636 [GS Search].

Araujo, F., Paes, E., & França, J. (2024). Introduzindo o pensamento computacional através de algoritmos no ensino fundamental: Uma experiência com alunos do 5º ano. *Anais do XXX Workshop de Informática na Escola*, 718–723. https://doi.org/10.5753/wie.2024.242337 [GS Search].

Battal, A., Afacan Adanır, G., & Gülbahar, Y. (2021). Computer science unplugged: A systematic literature review. *Journal of Educational Technology Systems*, *50*(1), 24–47. https://doi.org/10.1177/00472395211018801 [GS Search].

Berto, L. M., Zaina, L. A. M., & Sakata, T. C. (2019). Metodologia Para Ensino do Pensamento Computacional para Crianças Baseada na Alternância de Atividades Plugadas e Desplugadas. *Revista Brasileira de Informática na Educação*, *27*(2), 01–22. https://doi.org/10.5753/rbie.2019.27.02.01 [GS Search].

Boswell, P., & Boswell, A. (2017). Turing tumble: Build marble-powered computers (educator guide) [Link].

Brackmann, C. P. (2017). Desenvolvimento do pensamento computacional através de atividades desplugadas na educação básica [Link]. *Doutorado em Informática na Educação, Universidade Federal do Rio Grande do Sul.* [GS Search].

Brasil. (2022). *Computação na educação básica – complemento à BNCC* (tech. rep.) (Link). Ministério da Educação.

Braz, P., & Barcellos, R. (2024). Desenvolvimento do pensamento computacional em escolas públicas do ensino médio: Um relato de experiência. *Anais do XXX Workshop de Informática na Escola*, 449–460. https://doi.org/10.5753/wie.2024.242627 [GS Search].

Carvalho, F., & Braga, M. (2022). Pensamento computacional na educação brasileira: Um olhar segundo artigos do congresso brasileiro de informática na educação. *Revista Brasileira de Informática na Educação*, *30*, 237–261. https://doi.org/10.5753/rbie.2022.2649 [GS Search].

Chen, P., Yang, D., Metwally, A. H. S., Lavonen, J., & Wang, X. (2023). Fostering computational thinking through unplugged activities: A systematic literature review and meta-analysis. *International Journal of STEM Education*, *10*(1), 47. https://doi.org/10.1186/s40594-023-00434-7 [GS Search].

Cruz, M. K., Marques, S., Tavares, T., Oliveira, W., & Seelig, G. (2023). Normas, diretrizes e material didático para o ensino de computação na educação básica brasileira. *Anais do III Simpósio Brasileiro de Educação em Computação*, 337–346. https://doi.org/10.5753/educomp.2023.228332 [GS Search].

Feitoza, P., & Cunha, M. (2024). Uso da robótica como ferramenta pedagógica para ensino do pensamento computacional a alunos do ensino fundamental i: Um relato de experiência. *Anais do XXXV Simpósio Brasileiro de Informática na Educação*, 2273–2286. https://doi.org/10.5753/sbie.2024.242346 [GS Search].

Ferreira, L., Rodrigues, R., Raposo, E., Souza, X., Oliveira, A., & Trindade, G. (2025). Pensamento computacional no 1º ano do ensino fundamental: Explorando o bubble sort por meio da dança. *Anais do XXXIII Workshop sobre Educação em Computação*, 585–594. https://doi.org/10.5753/wei.2025.8360 [GS Search].

França, R., & Tedesco, P. (2021). Corporeidade, ludicidade e contação de história na promoção do pensamento computacional na escola. *Anais do Simpósio Brasileiro de Educação em Computação*, 132–142. https://doi.org/10.5753/educomp.2021.14479 [GS Search].

Garcia, S. R. J., & Borges, M. A. F. (2023). Recomendações para grupos que fomentam o pensamento computacional. *Anais do II Workshop de Pensamento Computacional e Inclusão*, 135–144. https://doi.org/10.5753/wpci.2023.236182 [GS Search].

Grover, S., & Pea, R. (2017, December). Computational thinking: A competency whose time has come. https://doi.org/10.5040/9781350057142.ch-003 [GS Search].

Guarda, G., & Silveira, I. (2023). Desafios e caminhos para a implementação da BNCC computação no ensino médio. *Anais do XXIX Workshop de Informática na Escola*, 798–809. https://doi.org/10.5753/wie.2023.232658 [GS Search].

Guimarães, M., Oliveira, P., Lucas, A., Oliveira, A., & Quintela, B. (2023). Estimulando o pensamento computacional a partir da computação desplugada: Uma abordagem para meninas do ensino fundamental. *Anais do II Workshop de Pensamento Computacional e Inclusão*, 87–96. https://doi.org/10.5753/wpci.2023.236139 [GS Search].

Hsu, M., & Rodrigues, R. (2025). Ensaios sobre a aplicação da arte de dobraduras e tangram para explorar o pensamento computacional e habilidades steam. *Anais do XXXIII Workshop sobre Educação em Computação*, 1403–1414. https://doi.org/10.5753/wei.2025.9395 [GS Search].

Katoningsih, S., & Mahadewi, I. (2023). Early childhood arithmetic learning assisted by marble game media. *Proceedings of the International Conference on Learning and Advanced Education (ICOLAE 2022)*, 996–1005. https://doi.org/10.2991/978-2-38476-086-2_84 [GS Search].

Kunovic, I., & Krzic, A. S. (2021). Comparison of students' motivation for programming computer game and educational robot using the game of marbles. *2021 44th International Convention on Information, Communication and Electronic Technology (MIPRO)*, 704–709. https://doi.org/10.23919/MIPRO52101.2021.9596790 [GS Search].

Lima, A. A., Oliveira, M. C., & Nunes, M. A. S. N. (2022). A transversalidade do pensamento computacional: Algumas justificativas. *Anais do I Workshop de Pensamento Computacional e Inclusão*, 73–85. https://doi.org/10.5753/wpci.2022.227528 [GS Search].

Martins, E. C., Silva, L. G. Z., & Neris, V. P. A. (2023). Systematic mapping of computational thinking in preschool children. *International Journal of Child-Computer Interaction*, *36*, 100566. https://doi.org/10.1016/j.ijcci.2023.100566 [GS Search].

Mourão, A., Jardim, H., Belarmino, D., Schirmer, L., Silva, A., & Melo, R. (2025). A computação desplugada como ferramenta para avaliação de conceitos de orientação a objetos no ensino superior. *Anais do V Simpósio Brasileiro de Educação em Computação*, 347–356. https://doi.org/10.5753/educomp.2025.5242 [GS Search].

Nunes, I., & França, R. (2025). Pensamento computacional para todas as idades: Uma análise comparativa do aprendizado de programação entre crianças e pessoas idosas. *Anais do XXXIII Workshop sobre Educação em Computação*, 971–981. https://doi.org/10.5753/wei.2025.8652 [GS Search].

Papanikolaou, D. (2026). Tectonic computation: Crafting logic through material and geometry. *Design Research Society Conference (DRS)*. https://doi.org/10.21606/drs.2026.2908 [GS Search].

Pitt, L. (2023). Turing tumble is Turing-complete. *Theoretical Computer Science*, *948*, 113734. https://doi.org/https://doi.org/10.1016/j.tcs.2023.113734 [GS Search].

Pontes, R., Santana, J., Perkusich, M., Barbosa, A., Gomes, V., Simões, M., & Camelo, C. (2019). Avaliação de ferramentas para ensino de programação para crianças e adolescentes. *Anais do XXV Workshop de Informática na Escola*, 744–752. https://doi.org/10.5753/cbie.wie.2019.744 [GS Search].

Quintela, B., Guimarães, M., Dias, L., Verly, A., & Oliveira, A. (2025). Teaching computational thinking main concepts with a marble-powered computer. *Anais do V Simpósio Brasileiro*

*de Educação em Computação*, 413–422. https://doi.org/10.5753/educomp.2025.5330 [GS Search].
Quintela, B., Silva, S., Esteves, L., Dias, L., Daniel, L., Guimarães, M. L., & Oliveira, A. (2024). Ferramentas e estratégias para aumentar a inclusão de gênero e raça na computação: Uma mapeamento sistemático. *Anais do XXXV Simpósio Brasileiro de Informática na Educação*, 2456–2468. https://doi.org/10.5753/sbie.2024.242550 [GS Search].
Rosa, Y., Reiser, R., Oliveira, P., Foss, L., Cavalheiro, S., Bois, A. D., Piana, C., & Mazzini, A. (2021). Pc-câmbio: Proposta de atividade lúdica e desplugada aplicando a metodologia do pensamento computacional. *Anais do Simpósio Brasileiro de Educação em Computação*, 227–236. https://doi.org/10.5753/educomp.2021.14489 [GS Search].
Santana, B., Chavez, C., & Bittencourt, R. (2021). Uma definição operacional para pensamento computacional. *Anais do Simpósio Brasileiro de Educação em Computação*, 93–103. https://doi.org/10.5753/educomp.2021.14475 [GS Search].
Silva, G., Pessoa, J., Magatti, I., Gonçalves, A., Garcia, K., Brandão, A., & Vittori, K. (2024). Newbot: Jogo educativo para o ensino do pensamento computacional. *Anais do XXXV Simpósio Brasileiro de Informática na Educação*, 3127–3138. https://doi.org/10.5753/sbie.2024.244629 [GS Search].
Story, U. (2024). *Educational resources for Turing Tumble* [Disponivel em: upperstory.com/resources/].
Twilton, R. (2022). Tumble together: Web-based emulator for the Turing Tumble [Acessed on: August 18, 2025]. https://tumble-together.herokuapp.com/
Wing, J. M. (2006). Computational thinking. *Communications of the ACM*, *49*(3), 33–35. https://doi.org/10.1145/1118178.1118215 [GS Search].
Yang, W., Ng, D. T. K., & Su, J. (2023). The impact of story-inspired programming on preschool children's computational thinking: A multi-group experiment. *Thinking Skills and Creativity*, *47*, 101218. https://doi.org/https://doi.org/10.1016/j.tsc.2022.101218 [GS Search].
Zhan, L., & Cheng, J. (2025). The relationship between multisensory stimulus-integrated foreign language learning models and students' psychological states and language skill development-an empirical analysis using the global learning assessment database. *Frontiers in Psychology*, *16*. https://doi.org/10.3389/fpsyg.2025.1639885 [GS Search].