Teaching Computational Thinking Main Concepts with a Marble-Powered Computer

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Abstract. *This paper presents an activity aimed at teaching the main concepts of Computational Thinking to high school students. Algorithmic structures such as conditionals and loops are presented playfully using a game that represents a marble-powered computer. The activities described herein were applied to two groups of 21 and 16 high school students during 40-minute sessions. Besides describing the activity, it is also discussed how it could be extended to cover the main necessary concepts related to Computational Thinking. Results show that the students were quickly engaged in the activity, and even with the short time, most of them were able to understand the concepts and solve the challenges, indicating it could be an interesting approach.*

1. Introduction

In October 2022, the Brazilian Ministry of Education (MEC) approved a complement to the Common National Curriculum Base (BNCC), introducing digital skills as a new curricular component in primary and secondary education [da Cruz et al. 2023]. One of the three main thematic axes is Computational Thinking (CT), defined as the ability to formulate and solve everyday problems using fundamental concepts of Computer Science, such as multi-level abstraction, data analysis, and logical reasoning [Wing 2006].

Although CT is considered a fundamental skill that should be taught to all students from the early years of education, nearly half of Brazilian public schools have yet to implement classes or projects related to it [CIEB 2022]. Computer Science Unplugged is an approach designed to teach CT without relying on digital tools. This method can be implemented in various ways, including cards, board games, storytelling, etc [Battal et al. 2021]. 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].

This paper presents an unplugged activity conducted with two distinct groups of high school students as part of a University extension workshop. The activity utilized storytelling and the marble-powered mechanical computer game *Turing Tumble* to teach

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.

The paper is structured as follows. Section 2 presents the theoretical background. Section 3 outlines the materials and methods, followed by results and discussion in Section 4 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:

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.

These 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, da 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.

Fundamental CT abilities for elementary and high school students are developed such as: **a) Computational Logic (EF05CO03)**: perform operations of negation, conjunction, and disjunction on logical statements; **b) 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; **c) Algorithms (EF15CO02)**: Build and simulate algorithms, independently or collaboratively, that solve simple and everyday problems using sequences, conditional selections, and instruction repetitions; **d) Decomposition (EF15CO04/EM13CO01)**: Apply the decomposition strategy to solve complex problems by breaking them into smaller parts, solving them, and combining their solutions; **e) Abstraction (EM13CO02)**: Explore and construct problem solutions through refinements, utilizing various levels of abstraction from specification to implementation.

3. Materials and Methods

The *Turing Tumble* workshop described in this paper uses storytelling to engage the students and introduce new parts of the game. This workshop has been briefly described in a previous work [Dias et al. 2024] and in this paper the authors present a more recent application of the workshop in detail including all the materials and methods and discuss the limitations and positive aspects. The workshop was structured to be applied in a variety of contexts, depending on student's age, number of participants, time and resources available. Here, we describe an activity conducted at the Federal University of Juiz de Fora (UFJF) in Brazil with two groups of high school students for 40 minutes each. The supporting material was developed and adapted by volunteer undergraduate and graduate students, who conducted the workshop alongside a professor.

3.1. Materials

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 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 releaser. 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 1.

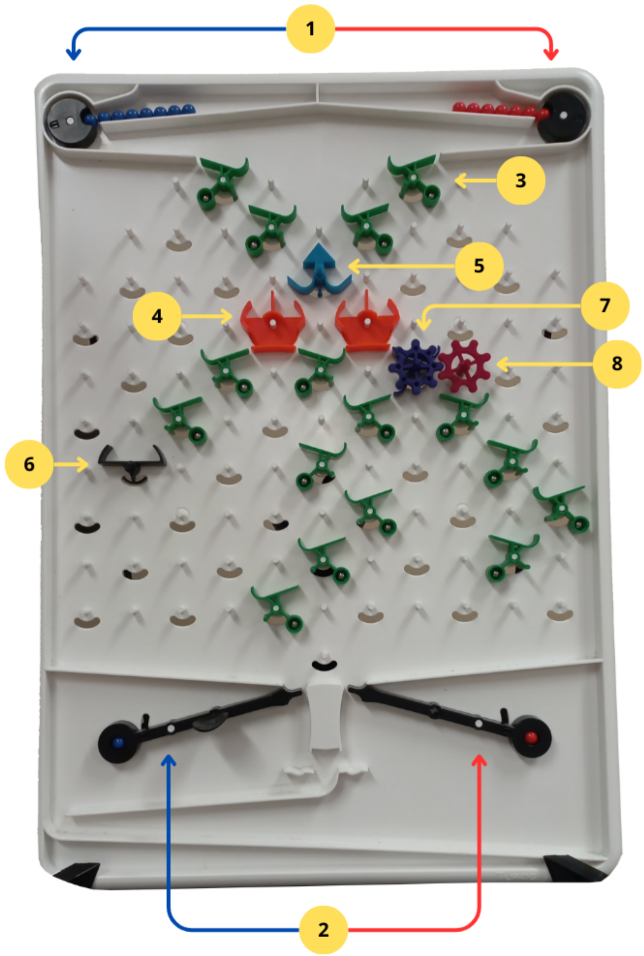


Figure 1. Turing Tumble board and parts.

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 (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 is 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 at the end of the workshops this information is shared among the participants so that they can continue solving the challenges in case they have access to a computer with internet connection.

#	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

Table 1. Relationship between the manageable parts, their representation or functions and their relationship to computational concepts

Materials used in this workshop include one copy of the Turing Tumble Game (Figure 2(c)), six A3 laminated paper copies of an art inspired by the board (Figure 2(b)) developed within this project by the authors and available for download [1], 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 2(a)) and is also available for download [2].

3.2. Methods

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

Upon receiving the participants, a relaxed conversation was held to understand the context in which the students live 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 4.

The activity begins with the introduction of the board and the first parts that are presented, which are the ramps (number 3 in Figure 1). Following the methodology proposed by the book that comes with the game, the first example is given partially solved

[1] https://drive.google.com/file/d/1K3ugpZMSdEluq3IjGNEP1kaAoW-kWVvo/view?usp=sharing
[2] https://www2.ufjf.br/meninasdigitaisufjf/oficinas/oficina-turingtumble/

with some of the ramps already positioned on the board. On the slideshow, the participants at this step can see the proposed challenge that consists of making only the blue balls fall, the board with part of the ramps already positioned and the number of missing ramps that could be used to solve the challenge. As this is the first example to understand the mechanism of the board, the participants can also see the shadow indicating where the missing parts should be positioned to complete this first example challenge. The participants are then invited to say out loud where the parts should go to make sure everyone understands the idea. Then, one of the volunteers puts the missing parts and presses the start button to run this first example and check if the challenge was solved.

After the first example is concluded, the participants are presented to the next challenge consisting of the expected results, the configuration of the board with some parts already placed on it and the parts that are allowed to be used to complete the challenge. The first challenge, for example, specifies that only 6 ramps can be used. The participants which are working in small groups are invited to draw on their respective laminated papers, using the felting tip pen, where they believe the parts should be placed to solve the challenge. At this moment, they are exercising their abstraction, training the ability to imagine all the steps the balls should take to arrive at the final configuration expected by the challenge.

The facilitators walk around the classroom while each group develop their solution on the laminated paper board, providing hints when needed. From this moment on, for the following challenges, one group at a time is invited to interact with the mechanical board when they believe a solution was found. In addition to presenting the draft solution, each student from the group is encouraged to interact with the board, either by adding one of the missing pieces or pressing the start button to verify if their solution worked as expected. After the execution, the students from all groups are invited to discuss the result and, if feasible, present corrections or alternative solutions.

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.

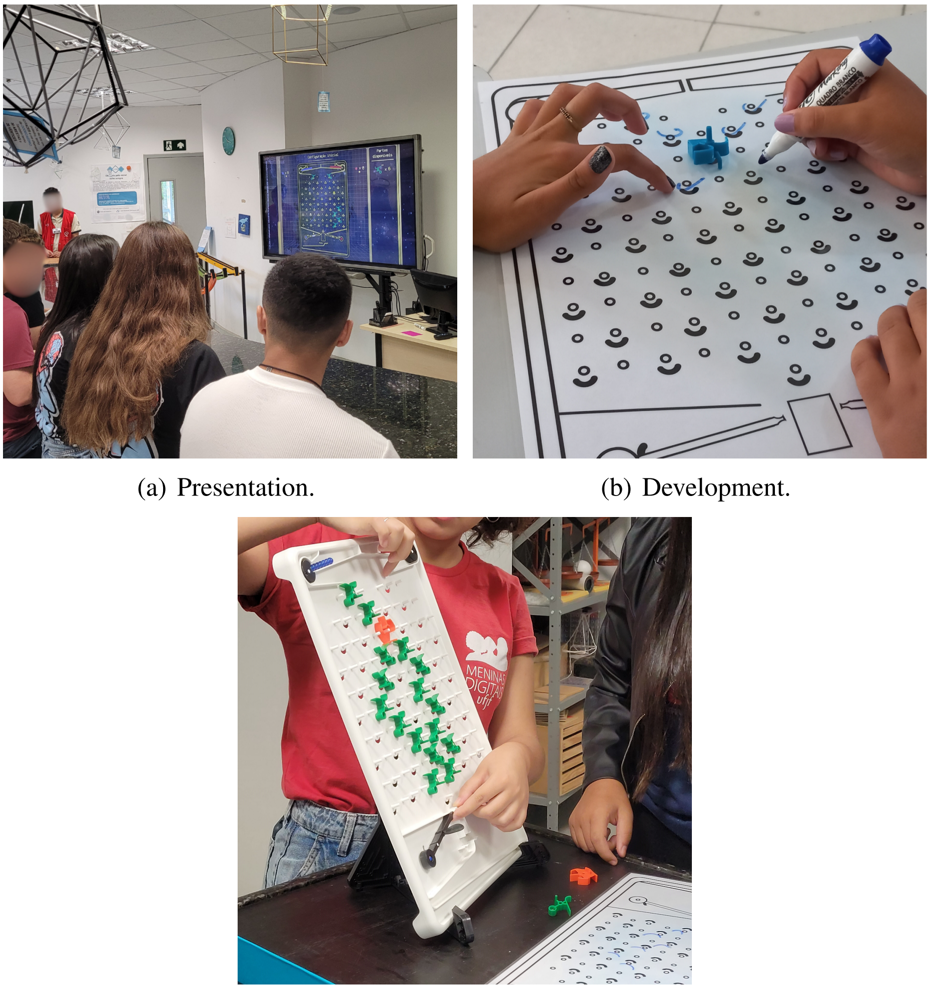
There are three moments in the resolution of the challenges, pictured in Figure 2.

Presentation (2(a)) 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);

Development (2(b)) Each group develops a solution on its laminated paper board knowing that there are multiple possible solutions;

Solution (2(c)) 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.

Throughout the process, the participants work with concepts related to the pillars of computational thinking, such as abstraction when using the laminated paper board



(a) Presentation. (b) Development.

(c) Simulation.

Figure 2. Activity dynamics in practice.

before testing on the real board, algorithms when deciding the placement of the parts and decomposition when thinking of each step of the solution in order 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.

4. Results

The activities were conducted as described in the subsection 3.2 in two separate classes (C1 and C2). C1 consisted of 16 students of which 9 were boys and 7 were girls, and C2, consisted of 12 boys and 9 girls, totaling 21 students. The participants in both classes were instructed to organize themselves into groups of up to four people, and they did so naturally, resulting in the groups described in Table 2.

Initially, no difference was observed in the performance of the groups in any of the classes, except in terms of conviction in their own abilities. In C1, the group formed only by girls pointed out, before solving the first challenge, that the activity was complex and difficult to carry out, but in the end they successfully completed all the challenges

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

Table 2. Quantitative of groups by gender and classroom.

without showing difficulty in comparison to the other groups as all the groups were able to solve the proposed challenges.

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 arm if positive and remain with their arm down in case of negative. The positive answers that were grouped by gender are shown in Table 3.

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

Table 3. 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.

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, during the activity which comments can be heard exposing the desire to start a degree in the areas of STEM. A C2 girl student reported at the end of the workshop that she had changed her mind during the activity 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 and the fact that the workshop was provided by women might have contributed to this participant manifesting this change on her initial response.

4.1. Limitations

One of the main limitations is the lack of a board for each group of students. Since the activity involved a group dynamic, the absence of individual boards caused some overload, as students had to share the available space and materials. The laminated A3 was developed and proposed to reduce this problem when working with larger classrooms.

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, keeping everyone engaged throughout the session.

Another 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.

As much as group work is necessary and a great learning experience, not everyone has the initiative to propose their ideas and no matter how much they participate, they would work better on the concepts if they carried out the activities alone. The fact of having a single replica of the board for implementing the solutions makes the class walk together and have to wait everyone to finalize their solutions on laminated paper copies. Along with the time constraints, not all groups can implement a complete solution on the board.

4.2. Positive Aspects and Educational Impact

The structure of the game, increasing the difficulty and introducing new parts, gradually creates a dynamic environment, where students remain engaged. At it is an unlimited game, the creativity flows and during the activity, several proposals for new challenges and solutions emerge in a relaxed and enthusiastic way, affirming the learning of the concepts. The stimuli of obtaining a correct result reinforces self-esteem and self-confidence, especially in high school, where the responsibility of choosing a career is a reason for insecurity and fear in the face of the expectation of meeting family, social and economic demands.

Moreover, the activity was offered by female undergraduate and graduate students and a female professor, which contributes to gender representation. Therefore, the impact extends the acquired Computational Thinking knowledge while also contributing to breaking gender stereotypes.

5. Conclusion

An unplugged activity using a marble-powered computer board game to teach Computational Thinking main concepts was presented. Due to the limitation of only having one edition of the game, an A3 laminated board was developed to allow the application of the activity for larger groups. A slideshow with the translation to Brazilian Portuguese of the story and challenges was also proposed and is available for download and reproduction of the activity.

During the activity, some questions aimed at assessing the prior knowledge of the high school participants revealed that most of them had already visited the University campus before, and plan to pursue an undergraduate degree there in the future. However, only 6 out of 37 participants answered that they were interested in pursuing a STEM-related course (4 girls and 2 boys).

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