The design and implementation of “unplugged” game-based learning in computing education*

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ABSTRACT

We share our experiences using an “unplugged” card game to introduce youth and adults to fundamental coding concepts and computational thinking (CT). In this game, players develop algorithmic thinking and understanding of constructs such as loops and conditional statements as they build and execute battle plans (“code”) in a pirate-themed card game. There are two factors that influence the game’s impact on learning: design and implementation. We describe how the game was designed to teach coding and CT, what actually happened when we tested it in outreach programs and in schools, and how we improved the connection between theoretical and actual effectiveness. One challenge was to improve the efficiency of teaching rules. Theoretically, players gain and master CT skills as they pursue game goals, but only when they correctly operate within the rule system. In practice, we saw that teaching the rules was taking an inordinate amount of time with diminishing returns as players became cognitively overloaded. Over several implementations, we generalized design principles that work for groups of different characteristics, including ages, size, and learning contexts. A key heuristic was to modify the game to introduce a practice round with reduced rules while not sacrificing playability. We also describe some gaps between play and learning that we could not bridge with the game alone, which revealed both its limitations and the importance of additional facilitation necessary to support learning.

CCS CONCEPTS

• Social and professional topics → Computing education; K-12 education; Computational thinking

KEYWORDS

Unplugged, tabletop games, game-based learning, outreach, formal education, secondary education

1 GAME-BASED LEARNING IN ACTION AND IN THEORY

#1: A group of 150 middle school girls sat in a large function room as guests of a well-known tech company. An energetic speaker announced that they would be playing a card game to learn coding without computers. Thirty minutes of rule explanation later, the game finally began. A group of girls began playing, but after a

short period, they started to check their phones in between turns. Many drew cards but did not play them to pursue the goals of the game.

#2: After calculating the result of his battle plan during the game, an 8-year old player commented, “This is a game of math. How is this programming?” Another boy could be seen making a mistake of adding numbers on three of his cards instead of simulating the battle plan as a step-by-step sequence of actions that loops two times.

#3: As players were eliminated one by one, the remaining 9 and 10 year old players invited the eliminated players to join them so that they could stay in the game. Each pair divided the cards between them and quietly discussed what cards to play on their turn.

The above vignettes came from our experiences implementing a pirate-themed card game that teaches coding concepts and develops computational thinking without assuming prior knowledge. The brief scenes were chosen to highlight several considerations in the design and implementation of tabletop game-based learning (GBL): (1) the importance of learning and following game rules, (2) the relationship between game mechanics and formation of mental models, and (3) the influence of sociocultural factors.

GBL broadly refers to the design and use of games (usually digital) and game-like elements to develop new skills and understandings [9, 15, 22]. A well designed game can be conceptualized as a structured, goal-oriented, feedback-driven experience that integrates the “work” of learning (gaining mastery) and the “fun” of play [12, 13]. When playing games, students can willingly (and often eagerly) acquire skills, knowledge, and dispositions, but only if the activity remains playful [13].

GBL is supported by theories on cognition, affect, motivation, and sociocultural factors, which cannot be easily separated from each other [15]. In vignette #1, the girls’ apparent lack of engagement could be due to low motivation (“Do I want to do this, and why?”) [8], or it could be due to uncertainty about how to play a game that seemingly required half an hour of rules explanation. By the end of the 30 minutes, some of the initial excitement might have changed to boredom (i.e., “affect”). Complexity is not a bad thing in a game. In fact, it is associated with challenge, which is inherently motivational [1]. However, if understanding complex rules overwhelms a player’s cognitive load, it could hinder learning the intended content or skills, as the player’s focus is on learning to play rather than playing to learn [3, 17].

According to one model of GBL, gameplay occurs in cycles of Challenge- Response-Feedback [5]. Although the main challenge is to achieve the win condition(s), there are often sub-challenges along the way. Players respond to various challenges by choosing from the options available to them within the rule system of the game. When making these decisions, players need to understand what they can and cannot do in order to get the proper feedback. Unlike digital games where the feedback mechanism is automatic and hidden, tabletop gamers enact the rules that provide feedback on their choices [10, 22]. Typically, players would hold each other accountable to correctly follow these rules to ensure not only accurate feedback but also that there is fairness as players compete to win. However, if a majority of the players are struggling to understand what the rules are, the cycles of Challenge-Response-Feedback are derailed, and learning is weakened.

Learning the rules does not only involve knowing when and how to perform actions such as drawing cards or rolling dice, but also comprehending and speaking the language of the game (i.e., “specialized vocabulary”). For instance, when learning the rules of chess, players need to know the names of the different pieces and how they move. For educational games, the targeted concepts or skills would also need to be introduced. Hence, supporting the learning of game rules and concepts is a key challenge for implementing GBL effectively.

In vignette #2, when we observed players' confusion about whether this was a math or coding game, we considered a possible cognitive mismatch in “learning mechanics” [15]. This refers to the integration of the primary actions that players perform in the game (“mechanics”) and the formation of a desired mental model (“learning”). In the vignette, the player action of executing battle plans (i.e., algorithms) did not lead to an accurate understanding of loops.

Finally, vignette #3 points to the usefulness of the sociocultural perspective for understanding how learning could be influenced by gameplay in at least three ways: (1) the development of player identities and discourse [9], (2) the impact of player interaction on affect and motivation, and (3) the inclusion of more experienced and knowledgeable players [17]. For instance, a player's game identity (i.e., pirate), the game's competitive elements (i.e., sink other players' ships), and “take-that” mechanics (i.e., steal other players' ships or battle plans) may influence how children of different characteristics (age, gender) play. Also, being aware of social factors that impact students' affect, interest, and motivation could inform how we design and implement games to mitigate negative influences. The inclusion of peer and adult facilitators may also affect learning and gameplay.

In the next section, we elaborate on the game's design concept, educational goals, and learning mechanics. In Section 3, we describe its use in outreach and formal education settings, what challenges we encountered, and how we improved implementation. We conclude by summarizing the lessons learned and key insights, and briefly discuss ongoing work to develop an innovative CT assessment instrument specifically designed to suit the dynamic and social characteristics of tabletop games.

2 GAME DESIGN

The Potato Pirates card game can be situated in a growing family of “unplugged” activities that teaches computing without computers. By sidestepping the technical challenges and distractions of using a computer device, participants can focus more on the thinking and concepts involved. The original Computer Science Unplugged (CSU) activities were characterized as kinesthetic and social, and take the form of puzzles, challenges, and stories [5]. They were designed to introduce the big ideas of computer science to a broad audience across age groups, without assuming any background knowledge. Tabletop games share many of these characteristics.

Existing tabletop games designed to teach computing concepts and computational thinking include: Robot Turtles, Robot Wars Coding Board Game, Code Master Programming Logic Game, Bits & bytes, Race condition, and Code Monkey Island. Researchers have also developed non-commercial games to support the learning of computational models and algorithmic thinking [e.g., 7, 10, 11, 18]. The majority of these games involve sequencing instructions to move objects on a gridded board to achieve various objectives.

Although the game designers for Potato Pirates had similar learning goals in mind, they also wanted a social and dynamic experience for the learners where they can compete or form allies with one another. They drew inspiration from card games such as Monopoly Deal and Exploding Kittens to create a social, interactive, and short duration tabletop gaming experience. Playing the game creates space for parents and kids, experts and beginners to come together to learn from each other, resonating with Papert's idea of transferring the positive aspects of the cultural-social experience of a samba (dance) school to the context of “traditional” learning [14].

In Potato Pirates, players assume the role of pirates and start with 2 ships each with 10 crew members (i.e., “potatoes”) per ship. To win the game, one can save the Potato King by collecting all 7 Potato King cards hidden randomly in the deck. A player can also win by eliminating other players in the game by sinking their ships. Achieving this latter objective involves making decisions that require understanding of coding concepts and the application of computational thinking.

While there are many definitions of CT, we have identified two that seem most relevant in stating the learning goals of this card game. Among the examples given by Wing [21] are algorithm building, simulation, and debugging. Based on their observations of kids creating Scratch projects, Brennan and Resnick [4] assembled a CT framework consisting of concepts, practices, and perspectives. The coding concepts addressed by the game are sequences, loops, conditionals, and data (variables).

During a turn, a player draws two cards and then choose an action: (1) create a battle plan with a maximum of three cards on a ship, (2) modify an existing plan, or (3) execute a previously planned attack. A battle plan consists of action cards and/or control cards. Action cards are named “Roast”, “Mash” or “Fry” that remove different numbers of potatoes from enemy ships. Players can also combine action cards with control cards such as “For” and “While” loops to power up the attacks. Figure 1 shows an example of a battle plan that combines two Roast cards and 1 Mash card to

remove a total of 4 potatoes from an enemy ship. Figure 2 shows a powered up attack that uses a For 3 times loop with a Roast and a Mash card. This battle plan executes Roast and Mash three times each for a total of removing up to 9 potatoes from a target ship.

Figure 1: Battle plan with only action cards

Figure 2: Battle plan with a For loop and two action cards

The core learning mechanic consists of building, modifying and executing battle plans, which involves algorithmic thinking and understanding of sequencing commands and fundamental control structures including loops and conditionals. Battle plans must wait an entire round before they can be executed. This is an intentional design choice to ensure that other players have time to "read" other players' battle plans (aka "code") and respond. Hence, a related learning mechanic is moving potato crew from one ship to another to avoid losing ships in anticipation of an attack. Performing this action indicates strategic reasoning based on correct mental simulations of other players' battle plans.

The concept of data is expressed as the number of potatoes on ships, which changes when battle plans are executed or by playing other cards. Variables appear on some of the loop cards, whose value depend on one's own number of ships or the number of cards

in a target player's hand. Table 1 summarizes how game components and gameplay relate to the CT practices and concepts.

Table 1. Potato Pirates Game and CT

Game component or action	CT concept or practice
Cards: For, While	Loop Boolean expression Variables
Cards: If/Else	Conditional Boolean expression
Felt balls representing potato crew	Data
Create or modify a battle plan	Algorithm building Debugging
Targeting and executing a battle plan	Simulation Debugging
Strategically moving potato crew from one ship to another	Simulation

As mentioned earlier, sociocultural and affective theories are particularly useful for understanding tabletop GBL, because of its emphasis on face-to-face player interactions. The quantity and type of player interactivity constitute design choices. Potato Pirates was designed to be highly interactive to keep players engaged in a variety of ways, some of which may negatively impact students' affect. One of the win conditions involves sinking all of the other players' ships by removing all of the ships' potatoes through targeted attacks. When all of a player's ships are sunk, the player is eliminated from the game and their cards are given to the victor. Even losing one ship could potentially trigger a desire for revenge. This clouding of judgment may escalate a negative mood in the group, leading some players (especially those who are younger or less emotionally mature) to "rage quit", thus derailing the game and potentially cause other players to lose interest. Conversely, fear of retaliation can cause deadlock in some groups, simulating a "cold war" where players never execute their battle plans. However, when players do not engage in the learning mechanic, the cognitive goals are undermined.

Another way to win the game is to collect Potato King cards. When a player randomly draws and reveals one of these cards, other players must salute the player. The last player to salute gives two potatoes to the player who drew the Potato King card. While this design choice was meant to keep players attentive, the "punishment" aspect and subjectivity in determining who is the last to salute may make the "loser" feel embarrassed or unfairly chosen.

"Surprise" cards also add a high level of interactivity to the game by providing players with defensive and offensive abilities that can be triggered any time. The "deny" cards are used to stop battle plans from being executed but can also be used to deny "deny" cards and other surprise attacks. Surprise cards allow a player to steal another player's ship ("hijack"), use another player's battle plan ("hack"), steal another player's cards ("loot"), or get benefits such as an additional ship or cards ("switch"). These names are part of the game jargon that fit the pirate theme or the coding theme.

Surprise cards are a big part of the "take that" mechanic, which some players enjoy but others find unappealing. The latter group of

players do not like to attack other players and do not like to be attacked in return. GBL researchers have theorized that players develop identities and discourses while playing games, and how these can be used to leverage learning [9]. But if a game's theme forces a player to assume an undesirable fictional identity and to adopt discourse that the player is uncomfortable with (i.e., jargon about destroying “cute” potatoes), the learning goals may be sidelined. On the other hand, playing surprise cards may be so engaging that it distracts players from performing the core learning mechanics.

A final aspect of game design worth noting is aesthetics. The graphics of Potato Pirates are cartoon drawings of potatoes with dark outlines and bright colors. The card edges are also rounded with gold tinted edges. The components are soft brown felt balls (representing potatoes) stored in a burlap drawstring bag. These are all intentional design choices to convey a child friendly aesthetic, and to soften the “destruction” theme. Some studies have shown that round shapes and warm colors induce positive emotions, which transfer to enhancements in learning [19]. However, it is difficult to generalize findings that were conducted using specific games and with a narrow range of learners.

3 IMPLEMENTATION DESIGN

In the previous section, we theorized what the game is supposed to teach, how the mechanics support the learning goals, and potential pitfalls. Now we describe what happened in various implementations and how we identified and responded to challenges.

3.1 Outreach program at a tech company

The lead author observed the game designers facilitate an outreach program to a large group of students at a leading tech company. In the 1.5 hour session, about 1/3 of the time was spent on learning to play, while students got increasingly restless.

When students finally began playing, many struggled to recall the rules. Even if they did remember that they can perform actions like draw and play cards, they may not recall what the game cards mean (i.e., coding concepts), what constraints they have (e.g., a battle plan can have a max of 3 cards), and what choices they have (i.e., build, modify, execute, move potatoes).

At this event, there was sufficient staff for each table to have its own facilitator who can correct and remind students of the rules, but one can imagine that staffing and time would be more limited in a typical classroom. Following the outreach program, we implemented the game in locations summarized in Table 2.

Table 2. Implementation Sites

Place	Students	Time
School #1	Ninth grade computing students (39)	2 hours to train 8 student facilitators 1.5 hour for whole class
Student Care Centre	4th grade - 7th grade students (15-20)	1 hour per Saturday over 4 weeks
School #2	Entire cohort of 270 8th grade students played in different rooms. Groups ranged from 40 to 120 students.	1.5 hour

3.2 Ninth grade Computing Subject

The first in-school implementation took place in a 9th grade computing subject. To reduce cognitive load from having to learn many complex rules, card information, and available choices, we trained student facilitators to assist at each table. To focus students' attention on learning the coding concepts and more explicitly engage in CT, we designed two rounds for the game. In round 1, students only played with the action and control cards. This meant that they could only build and execute battle plans.

The game designers were initially hesitant with the modifications. It would lobotomize the game as players would have no way to prevent attacks. They were concerned that the game would lose its fun factor and balance.

To address these concerns, the plan was to add the remaining cards in round 2 so students could experience the game in its full richness as intended by the game designers. Dividing up the game into two rounds also meant that only half the rules would need to be explained at a time, lowering cognitive load as well as requiring less effort to hold students' attention. To further engage students' interest, we used the short, animated instructional videos created by the game designers. To verify that students have correctly learned the key rules, we created some T/F statements to check for understanding.

During Round 1, student facilitators were instructed to sit out of the game. Since it was a practice round that focused on building and executing battle plans, their job was to make sure that their peers understood the types of cards and how to use them. We observed that student facilitators were eager to share their expertise as they coached each player on possible combos they could make, without being explicitly told to assume this “advisor” role. We were struck by their willingness to share knowledge with their peers, even though it would mean giving up some competitive edge. As a result of the student facilitators' coaching, their peers were able to quickly learn the game and many were building advanced battle plans containing nested control cards by the end of the first round.

Round 1 ended fairly quickly because there was no way to stop the attacks, but this was according to design as the purpose was to practice the learning mechanics. Before Round 2 began, "advanced war tactics" (nested control statements) and the remaining categories of cards were introduced. These cards included the ability to stop attacks and sabotage players, and introduced a new win condition. Student facilitators joined in playing this round.

Training student facilitators was more effective than expected. First, it allowed us to pilot the game with a small group of students so we could confirm the effectiveness of the learning mechanics and try out different variations to scaffold the learn-to-play process. Also, when told that they would be helping us facilitate the game, the students took ownership of the process by assigning themselves to groups. They seemed eager to share the game with their peers and felt confident to do so by the end of the two one-hour training sessions.

3.3 Student Care Centre

Our second implementation was at a student care centre, where school-age children received out of school care and enrichment activities. Students between 4th grade to 7th grade played the game for 1 hour per Saturday over 4 weeks. The activities at the centre were mainly led by college-bound or university students recruited by a computer science lecturer. There were also adults from the community. All the volunteers were called "tutors". The lead author trained the tutors by teaching them to play the game. Then we reflected together on how to introduce the game to students. Without any prompting, the tutors saw the need to scaffold by having the students play with a partial deck initially and gradually introducing more cards over the 4 weeks of the program. The tutors selected categories of cards based on their knowledge of the students' social, emotional and cognitive levels. For instance, they were aware that some of the "take that" (sabotage) elements might lead to some of the kids getting upset. Also, students would likely struggle to understand the while loop card the most, so those cards were set aside for the final week.

These decisions contrasted with the modifications made for the 9th grade computing class. Given the 9th graders' coding experience and age, they were expected to learn all the coding concepts at once (in a single round). Calibrating the difficulty level of a game so that players can succeed but with some struggle is similar to designing learning that aims for a player's zone of proximal development [19].

The game was taught by the facilitators in small groups. Each group had its own facilitator that remained with that group for at least two of the 4 weeks. The lead author observed a group consisting of the youngest students for three of the four sessions. For this group of 4th-5th graders, the tutor played a key role. The tutor needed to individually help the younger students understand what the cards meant and guided them on how to put together a battle plan. Sometimes the tutor arranged the cards in different ways and asked the player to predict what each set would do and to select one to play. The tutor also modeled how to watch out for what other players were doing and what others' battle plans might do to one's own ships. Ships with more powerful attacks naturally became targets. The tutor walked students through executing a battle plan. Interestingly, the tutor tended to transform the code

execution into a mathematical procedure - i.e., first add the potatoes on the two action cards, then multiply this sum by the number on the "For"- loop card. When a student attempted to build a battle plan with two For-loop cards and one action card, she tried to figure out the right mathematical operations rather than execute the plan as a sequence of repeated actions that are in turn repeated.

3.4 Eighth Grade Outreach

A computing teacher at a secondary school initiated and organized an outreach to the entire 8th grade cohort of 270 students to play the game. We applied many of the lessons from the previous implementations. We also included a "capture most potatoes" goal as a win condition in Round 1, which was a good motivator for students to learn how to use the action and control cards to build powerful attacks. We proposed training student facilitators but was not able to do so. We also downloaded the instructional videos in advance to avoid potential internet connection problems.

Despite not having student facilitators, students needed little help after the rule explanations. One reason could be that I (lead author) became more experienced at explaining the rules clearly and efficiently; another could be that the improvements from earlier implementations transferred well. During the Round 1 debrief, we asked students to share the highest score in their group and then identified the student with the highest score in the room. The acknowledgement seemed to contribute to maintaining the excitement as we moved into Round 2.

It was difficult to get the students to settle down in between rounds so it was very useful that their teacher was present to silence the class so that we were able to quickly move on to explaining the new rules for the second round.

Students were highly engaged. There were several remarks after the session ended from students who wanted to play again and asked when they could do so. During the session, there was plenty of laughter, rise in volume of voices that indicated excitement, or quiet when players were concentrating on playing a turn or attentively watching other players take their turns.

While we avoided problems with loading videos from the Youtube website by downloading them in advance, some time was wasted by having to click on videos individually. It would have gone more smoothly to arrange them in an ordered playlist. It was useful to pause at select times to review how certain cards work. But as a general rule, we kept these explanations as short as possible because these were times when students were most likely to get restless. While it was important for students to learn the correct rules, there were diminishing returns the longer this time drags out. Spending more time on rules also meant having less time to play. It was interesting to observe some students consulting the rulebook, which we had forgotten was included in each box. Explicitly pointing students to this resource would teach them to help themselves, so that less time could be spent going over every detail of the game.

The game designers experienced more challenges because of the larger size groups they were working with. They had one group of 40 students in a classroom, approximately 60 in a dance studio, and over 100 students in the sports hall. The facilitators followed our practice of playing the game over two rounds and observed that this

was effective for reducing cognitive load from having to learn too many rules at once. Students also made fewer mistakes. They used the time in between rounds to clarify rules and quiz the students on the coding concepts. The team also observed that for students who did not have any coding experience, the concepts appeared to be math rather than code - that is, students performed operations like adding and multiplying to get the number of potatoes that a given battle plan would remove from an enemy ship.

The largest group of students, which was over 100, was the hardest group to manage and had the lowest engagement, especially the students along the edges and farthest away from the facilitators. The stuffiness in the room also made the students uncomfortable and restless. Many groups required one of the facilitators to sit in to get them interested in playing the game. After playing a round with the group, the students would usually be able to continue on their own. The facilitators observed that some groups were playing the game completely wrong, yet still seemed to be having fun. Once students were given the game boxes, they were immediately distracted and stopped listening to the rule explanation. Some groups seemed hesitant to attack each other for fear of retaliation.

4 DISCUSSION

While students can have fun without correctly following the rules, games are designed in such a way that operating correctly within the rule system facilitates the GBL Challenge-Response-Feedback cycle. Therefore, "learn-to-play" is a critical step before "play-to-learn" can be effective. Yet rules explanation can be a tedious and boring process for students so this step needs to be done efficiently. We have discovered that the following strategies work well:

- Pilot the game with a small group first to see how players enjoy the game and to identify core learning mechanics.
- Design a practice round that focuses students' attention on performing the learning mechanics.
- Experiment with different ways to modify the game to draw out key learning concepts and to adjust the difficulty level to suit the players' age, background knowledge, cognitive and emotional development and other relevant characteristics.
- When introducing rules over several rounds, make sure that the initial practice rounds still feel like a game - that is, they should still have a win condition that players are trying to reach.
- To make the most use of limited play time, train student or adult facilitators in advance so that each group has one experienced player.
- For younger players or when there are many participants, small group facilitation is even more critical.
- Use short instructional videos, especially to demonstrate how a turn works. Visuals are very helpful.
- Provide a rulebook as a reference guide but this should be a backup, not the primary way that students learn to play a game.
- If conducting the game in a school, having an authority figure who can quickly quiet the students is a great help to avoid wasting time and to reduce frustration.

We were pleasantly surprised to observe very little negative impact on affect from the pirate theme or the "take that" mechanics. In fact, both boys and girls across a wide age range seemed to enjoy the "destroy" and "sabotage" aspects of the game. When players were eliminated, we observed cases where they paired up with players still in the game or were still engaged as observers as they participated socially by commenting or offering advice and encouragement.

There were some interesting gaps between intended learning of coding concepts and development of students' mental model. Specifically, almost all students (and even adults facilitators) reduced the execution of battle plans involving "For" loops to a mathematical calculation. While this was sufficient to determining the correct number of potatoes to remove from a target ship, it was not a correct mental model for simulating code execution. The game context alone was not able to correct the misconception.

Another unresolved issue was balancing "fun" and "learning". There were game elements that did not directly develop computational thinking. They functioned as a kind of leveler so that the students who struggled with the coding concepts were still able to do well in the game. In an outreach setting, it is perhaps not critical to ensure that students learn the concepts. But in a classroom, there may be more pressure to make sure that time is spent on performing learning mechanics where CT is most present. Playing surprise or Potato King cards has more entertainment than educational value. When designing for classroom use, one has to be mindful of the trade-off. A game could be used poorly if all its "fun" is stripped away.

5 CONCLUSION

This paper documented what we learned from several instances of having school age children and youth play a card game designed to "teach coding without computers". We emphasized the role of effective teaching of rules ("learning to play") in order to support GBL adapted for tabletop gaming through iterations of Challenge-Response-Feedback ("playing to learn"). We also noted issues that require further investigation, including how players build mental models of code execution and how educators negotiate tension between "fun" and "learning" in formal education settings. We hope that sharing these experiences have sparked interest within the research and education community to conduct further studies of tabletop game-based learning in computing education.

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