# Design Principles for Serious Video Games in Mathematics Education: From Theory to Practice

Konstantinos Chorianopoulos[1,2], Michail N. Giannakos[2]
[1]Ionian University, Corfu, Greece, choko@acm.org
[*2]Norwegian University of Science and Technology (NTNU), Trondheim, Norway, mgiannakos@acm.org

## *Abstract*

*There is growing interest in the employment of serious video games in science education, but there are no clear design principles. After surveying previous work in serious video game design, we highlighted the following design principles: 1) engage the students with narrative (hero, story), 2) employ familiar gameplay mechanics from popular video games, 3) engage students into constructive trial and error game-play and 4) situate collaborative learning. As illustrated examples we designed two math video games targeted to primary education students. The gameplay of the math video games embeds addition operations in a seamless way, which has been inspired by that of classic platform games. In this way, the students are adding numbers as part of popular gameplay mechanics and as a means to reach the video game objective, rather than as an end in itself. The employment of well-defined principles in the design of math video games should facilitate the evaluation of learning effectiveness by researchers. Moreover, educators can deploy alternative versions of the games in order to engage students with diverse learning styles. For example, some students might be motived and benefited by narrative, while others by collaboration, because it is unlikely that one type of serious video game might fit all learning styles. The proposed principles are not meant to be an exhaustive list, but a starting point for extending the list and applying them in other cases of serious video games beyond mathematics and learning.*

**Keywords:** *Design Principles, Education, Guidelines, Mathematics, Interaction Design, Serious Video Games.*

## 1. Introduction

In this article, we propose the systematic design of serious video-games based on a few established design principles and we provide two case studies for mathematics education. Contemporary research on the design of serious games has focused mainly on the usability of educational video games [30], but usability does not regard students' engagement and domain learning. In this work, we explore the design of serious video games for mathematics education. This perspective is crucial for all students and especially to low performers and those with fewer opportunities in formal learning. Serious video games have been proposed as a means to engage students with a particular focus on the Science, Technology, Engineering and Mathematics (STEM) curricula. However, limited research has been conducted on the effectiveness and usability of serious game elements, and how these issues can be improved using the appropriate design principles. Design principles is one of the most important issues in serious games for learning, since their integration in most of the times is limited and inadequate (e.g., [1] [12] [21]).

There is a variety of design principles for video-games [7], as well as for educational games in the literature [3] [4] [10] [25] and many times design principles are conflicting each other, however they can also co-exist in serious games [13]. In this work, we attempt to shed light into some crucial design principles for enriching serious video games with the appropriate design elements.

Our methodology is user-centered and considers the elaborate design of serious games. The first case study is named "Gem-Game" and focuses on students' attending the middle school (called

Gymnasium in Greece). In the second case study, we are introducing a serious game that in addition to the above design principles introduces the property of collaboration, which is very important in learning and entertainment. In this work, we do not evaluate the effect of those games on attitudes and learning, which is an important topic for further research.
The rest of paper is structured as follows: in the next section, the design principles for serious video games are outlined based on a literature review of related works; the third section presents the case studies, while the last section summarizes the findings of the paper and makes recommendations for applying the design principles for serious video games in STEM education

## 2. *Design Principles for Serious video games*

Many researchers and educators advocate the use of video games for learning purposes. Studies have indicated that playing video games gives learners a ‘‘mental workout’’ and the structure of activities embedded in video games develops a number of cognitive skills [15]. Researchers in interaction design have highlighted the need for designing meaningful and playful learning applications since the emergence of interactive multimedia [28]. Moreover, the emergence of serious video-games has facilitated the wider adoption of learner-centered education and other changes in educational practices.
Previous research has claimed that a game’s story can motivate students to use an educational game [5]. Within the field of game design, narration is beneficial into a learning environment [18] [22] and provides opportunities for reflection, evaluation, illustration, exemplification and inquiry, especially on arithmetical concepts. Thus, our first design pattern is based on a narrative format, which is reinforced by the presence of a main hero controlled by the game player.
Previous work on the educational use of video games has also highlighted strategies for employing popular commercial games (e.g., Rovio’s Angry Birds) in a Physics course [26], but is has not provided any actual implementation of the respective concepts. This is often referred to as “low hanging fruits” and it is an established strategy towards serious game design. Thus, our second design is the use of familiar interactions and successful game mechanics from popular video game formats (e.g., platform games).
The third principle is grounded on people’s ability to learn from meaningful experiences. By getting immediate feedback during those experiences they can recognize and assess their errors and see exactly their mistake [11]. It is very important to recognize their exact mistake and identify what they could have done differently. We refer to this principle as constructive trial and error gameplay.
Last but not least, Computer-Supported Collaborative Learning (CSCL) environments have shown to positively influence learning (e.g, [20]). The collaborative interaction between learners can lead to further elaboration and refinement of individually constructed schemata, since it (1) incites learners to make explicit the actual level of schema development, and (2) demands them to explicitly compare their own schemata with schemata of others as to defend or criticize [14].
Rieber [24] and Dondlinger [8] have provided a list of generic design principles that in some parts overlaps with those in Table 1 for serious video games, but there has not been any formal application of those principles in video games for math education. In this way, we have designed several math video games in Scratch. In the following section, the video games are available online for further improvement by the Scratch community[12].

[1] Gem Game: http://scratch.mit.edu/projects/10181336/

[2] Grandma’s Garden Game: http://scratch.mit.edu/projects/18999509/

**Table 1.** Design principles for serious video games in mathematics education

| Theory | Design Principle | Source |
|---|---|---|
| Hero and narrative | Engage students with narrative (hero, story) | [18] |
| Familiar interactions | Engage students with familiar video game mechanics | [24] |
| Trial and error | Each error is an opportunity to try again | [11] |
| Collaboration | Engage students with collaborative learning | [20] |

The proposed design principles (Table 1) have been identified in a survey of related work and have been applied in the design of two math video games, which are presented in the following sections. Nevertheless, the proposed design principles are not an exhaustive list and researchers are encouraged to apply them in other types of serious video games, as well as to extend them with more principles.

## 3. Applying the Design Principles in Math Video Games

We consider that the design of a meaningful game is both art and craft. Although it is difficult to provide design principles for the art part, there are some design principles with regard to the craft aspect of a video game. Besides the principles, we consider that the game design space should be mostly motivated by a pragmatic need, which is defined by the teacher. Then, the teacher should be supported with tools and guidelines, in order to produce a video game that has a traceable design and that could be improved. Therefore, teachers who have knowledge in the respective content (course), technology, and pedagogy (students' needs) could design meaningful games. The online Scratch environment is ideal for the development of educational video games, because it supports an accessible programming environment and language, as well as versioning and collaborative development. In the following sections, we are describing the application of the design principles in the development of two math video games.

### 3.1. Hero and narrative

The illustrated game has a plot that starts with a small story and a mission is assigned to the player. The story and the mission are used to stimulate the students' interest and motivate them to play the game. We tried to make the dialogs and the plot funny. Storytelling is a universal method for engaging people through a few archetypes, such as hero, enemy, mentor, quest, and final resolution [6]. According to Vogler [32] each storytelling game consists of some common stages; our game's design (Figure 1) follows Vogler's storytelling structure. In the first stage, the hero is situated in the ordinary world; in our game the hero named Peter is in his bedroom and looking for his dog. Then the hero is presented with a problem or event that necessitates leaving the comfort of the ordinary world, Peter's dog, Lucky has been kidnapped. Next, the hero meets the fairy that guides Peter to collect 30 diamonds. Once the hero commits to the adventure, he begins the problem-solving process. During this process, the hero encounters various challenges that must be overcome in order to progress. In this stage Peter has to play and win the game in order to collect the necessary diamonds. Nevertheless, the narrative structure of the Gem Game is far from complete, because it lacks some important elements such as cut-scenes that link the game levels together. When Peter has collected the diamonds, the fairy appears and calls the witch, who gets the diamonds and releases the dog.


**Figure 1.** The narrative of the game unfolds from an intro scene, where the hero is informed about his missing dog, through the stages, and up to the final climax, where the hero retrieves his dog

## *3.2. Familiar interactions*

The gameplay of Gem Game is inspired by the classic side-scroller video game Scramble by Konami (figure 2). In comparison to the original Scramble video-game there is only vertical movement (figure 2). We wanted the game to be interesting and pleasant, so that it would not look like rigid book or computer-based exercises, which usually have a multiple-choice presentation format. For this purpose, we employed gameplay mechanics inspired by popular video game formats, such as side-scroller arcade games. The game is targeted to children that attend first and second grade of Gymnasium (Middle School) (13-14 years old). The main goal of Gem-Game is to improve the mathematical skills of players. The required skill-set refers to a mathematics unit on the addition and subtraction of positive and negative numbers. The first level includes addition and subtraction of positive numbers, the second is concerned with the addition and subtraction of negative numbers and the third with both operations with signed numbers.

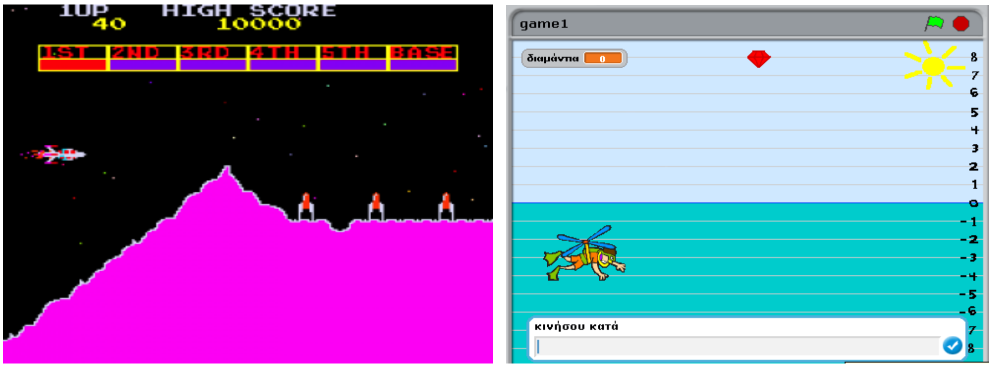


**Figure 2.** The gameplay of the Gem Game is inspired by the classic side-scroller video game Scramble by Konami

Besides video games, video-based courses have approached the teaching of this math module in a spatial way. For example, the respective video on Khan Academy is using an axis in order to visualize the special relationship between negative and positive numbers, as a cornerstone in learning to add them (figure 3). Other math games are using real world metaphors in order to assist students' understanding of the negative numbers concept (Figure 3).

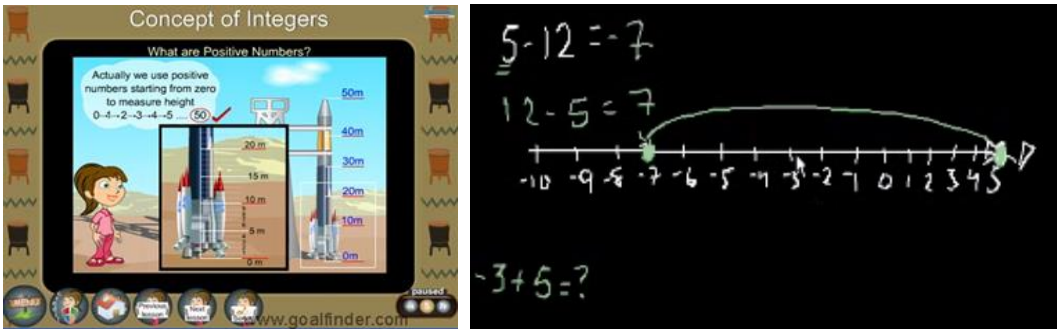


**Figure 3.** Video lecture on the topic of adding signed numbers employs a spatial representation of the numbers, but it is not interactive.

The main character of Gem-Game (Peter) moves vertically according to the operation executed by the player. So the students also get a spatial idea of upwards movement when adding and downwards movement when subtracting (figure 4). In particular, the player has to correctly add/subtract in order to reach each diamond that scrolls horizontally from right to left. For example, if the player is positioned on line 6, and the diamond is on line 1, the player must write -5 in order to reach the diamond.


**Figure 4.** The first stage has only positive integers, the second stage has only negative integers, and the last stage has both positive and negative integers

The player must go through three different levels (figure 4). The first level has only positive integers, the second level has only negative integers, and the last level has both positive and negative integers. Moreover, at each stage the main character wears a different uniform: a flyer uniform in the first stage; a diver uniform in second stage; and a helicopter uniform in the third stage.

### 3.3. Constructive Trial and Error

Notably, when the player makes an addition or subtraction he receives immediate feedback (since the hero is being moved on the respective line), in case this numerical operation is a mistaken one the students will receive a constructive feedback, and will be able to continue by typing a correction from the new position. In the following example (Figure 5), if the player had typed +4, then the player only needs to type +1 in order to get the diamond. The player completes each level by collecting 10 diamonds.

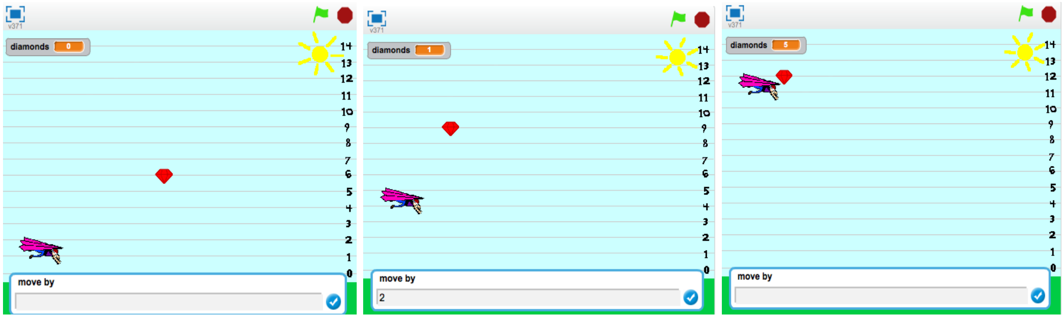


**Figure 5.** It is possible to provide the right answer by thinking spatially and by trial and error, just by counting the steps required to move from the hero position to the one of the diamond, so if the player makes a mistake, it is a constructive one, because the player can continue by typing a correction from the new position

### *3.4. Collaborative learning*

There are various support mechanisms that could structure collaboration during game play. Kirschner et al., [20] successfully added structure by presenting roles to students; Owen [23] by setting clear boundaries in terms of time and number of contributions; and Kirschner et al., [20] by providing a negotiation tool to support the process of finding common ground in problem-solving groups. Following the basic collaborative learning scripts, we attempted to utilize them in a mathematics video game named “Grandma’s Garden” (Figure 6). One of the challenges in the gameplay of this serious video game was the need for real-time action, without typing in the moves in a dialog box, which was employed in the Gem Game.

The main goal of the Grandma’s Garden Game ([http://scratch.mit.edu/projects/18999509/](http://scratch.mit.edu/projects/18999509/)) is to type in the correct number of yellow leaves collected during the gameplay. In order to do so, the players have to count in their heads the number of leaves each one collects and then make a final addition in order to report it to Grandma (Figure 7). In this way, each player practices addition and deletion and is accountable to the second player, because they can only win if each one keeps the correct count and only if they make the final addition correctly together. The current version of the game only supports addition and deletion by steps of one, but it is easy to update the game in order to support addition and deletion of greater numbers, which correspond to visually larger/different leaves and flowers.

The gameplay mechanics are inspired by single-screen falling blocks video games, such as Nintendo’s Wario’s Woods, where the player controls a character that collects falling blocks. Notably, this game takes into account all previous design principles (heroes and narrative, familiar interaction style, constructive trial and error) and also applies the principle of two-player collaboration.

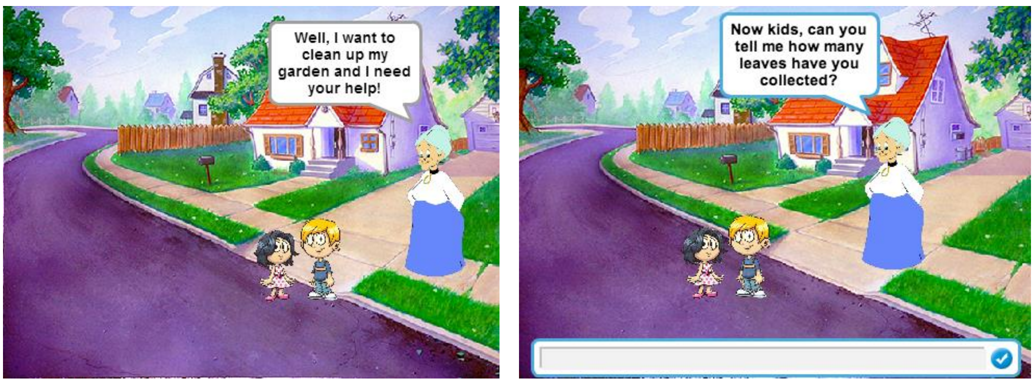


**Figure 6.** The introduction of the main characters of the “Grandma's Garden Game”: Grandma is motivating the two heroes (Alice and Bob) to help her clean-up the garden

**Figure 7.** The game only provides minimal feedback (left) because the counting takes place in the heads of the players and between them. The only feedback provided by the game is “+1” for a yellow leaf (right) or “-1” for a flower, which appears just next to the head of the heroes, when they collect the respective item. In this way the players are motivated to collaborate not only on screen but in real life too

## 4. Conclusion and further research

In this work we proposed design principles for employing serious video games mathematics education. The proposed principles have been based in related work that has analyzed popular video games, so it provides an assurance of their validity to engage students with interesting stories and gameplay. In particular, after identifying those principles, we also applied them in the field of two mathematics video games with illustrated examples. Previous research has considered similar design guidelines for the case of serious games for medical purposes (e.g., Re-mission games), but there has been limited work on mathematics education. Besides mathematics and medicine, serious video games have been developed for many sensitive fields, such as sustainability and civic engagement.

In addition to the aforementioned games, we have applied the design principles in the development of several more serious games for mathematics. The Underwater Math[3] and Math in Space game[4] (Figure 8) provide players with a target score, which can be reached by collecting starfish, or stars respectively. The gameplay of these video games has been inspired by Atari’s Asteroids video game, but there is no shooting in our case. Although they do not include the constructive feedback design principle, both of them include the threat of an enemy: a shark, or a meteorite respectively.


**Figure 8.** Underwater Math (left) and Math in Space (right) are two more serious games that have been developed by following the design principles

In future versions of these games, we plan to change the behavior of the enemy in order to affect the score instead of ending the current round. In other words, our vision is to make the notion of

[3] Underwater Math: http://scratch.mit.edu/projects/14465771/

[4] Math in Space: http://scratch.mit.edu/projects/10276581/

"game over" irrelevant and to focus on encouraging the player to make more calculations even if some of them are not correct on the first try. In addition, we plan to revise these two games to include the rest of the design principles: a story line, as well as collaborative modes of playing. In our view, the most challenging principles of designing serious video games for educational goals is the gameplay and the constructive trial and error. As soon as the embedding of the design principles in the video games has been concluded, the next step is to actually evaluate the learning effectiveness of alternative versions of the video games for diverse types of students and learning styles. For example, some students might be benefited by collaborative play, while others might prefer more story than gameplay. Therefore, further research should evaluate the effectiveness of each design principle as well as combinations of them for diverse learning styles.

On the other hand, traditional instruction is an emotional, social, and cognitive experience in which teachers use their knowledge, voice, and movement to address the learners with questions and stories. We do not expect or suggest that serious video games replace face-to-face teaching and learning. Nevertheless, it is important to use a variety of teaching tools and practices beyond the traditional teaching in order to facilitate the full spectrum of learning styles. The design principles can be used by designers, educators, practitioners and researchers in the area of technology-enhanced learning. In addition, can be also evaluated in order to ensure their validity and seek suggestions and extensions.

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