Design Principles for Serious Games in Mathematics

Konstantinos Chorianopoulos
Ionian University
Corfu, Greece
choko@acm.org

Michail N. Giannakos
Norwegian University of Science and Technology (NTNU)
Trondheim, Norway
mgiannakos@acm.org

Nikos Chrisochoides
Old Dominion University
Norfolk, VA, USA
nikos@cs.wm.edu

ABSTRACT
Although there has been a lot of interest in the employment of video games in education, there are no clear design guidelines. In this work, after surveying previous work in video game design, we highlighted three design principles: 1) engage the students with a story and a hero, 2) employ familiar game mechanics from popular video games, and 3) provide constructive trial and error gameplay for learning. As an illustrating example of those principles, we designed a video game that teaches addition and subtraction of signed numbers. Finally, we outline several more serious games that have adopted the above design principles. The results should be useful for designers, teachers, and researchers who work in the area of serious games for learning. Further research should extend and experimentally validate these principles according to the discipline and the learning style of students.

Categories and Subject Descriptors
K.3.1 [**Computer Uses in Education**] Computer-assisted instruction (CAI); K.3.2 [**Computer and Information Science Education**]: Computer Science Education, Curriculum;

General Terms
Design, Human Factors.

Keywords
Interaction Design, Serious Games, Learning, Mathematics, Design Principles.

1. INTRODUCTION
Contemporary research in interaction design for learning has focused mainly on the usability of the computer-based learning applications. Our thesis is that any learning environment (formal or informal) requires a consideration also for qualitative aspects, such as engagement and experience. In this work, we are exploring alternative learning styles through the design of a serious video game. A fundamental principle of meaningful education is that all students can learn if the appropriate personalized conditions are given to them (Robinson 2009). Research into multiple learning styles confirms that students learn in many different ways (Murphy 1992, Spalter et al. 2000). This perspective is crucial for all students and especially to low performers and those with few 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) curriculum. However, limited research has been conducted on the effectiveness of serious game elements and the respective teaching practices. In particular, there is limited understanding of pragmatic design principles for serious video games. As such, in the current work we attempt to shed light into design principles for enriching serious video games with the appropriate design elements and learning practices.

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Our methodology is user-centered and considers the elaborate design of a serious games and their application in learning. In collaboration with math and informatics teachers, we designed and developed a math video game. The serious video game is named "Gem-Game" and it is targeted to children that attend first and second class of Gymnasium (middle school).

The rest of paper is structured as follows: in the next section, the design principles for serious video games are outlined; the third section presents the game design of our case study, while the last section summarizes the findings of the paper and makes recommendations for adopting design principles for serious video games in learning.

2. DESIGN GUIDELINES
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 (Johnson 2005). Researchers in interaction design have highlighted the need for designing meaningful and playful learning applications since the emergence of interactive multimedia (Soloway et al. 1994). Moreover, the emergence of serious video-games has facilitated the wider adoption of learner-centered education and other changes in educational practices.

The use of educational video-games can be effective only if elements such as goals, competition, challenges, and fantasy influence motivation and facilitate learning. Motivation refers to the initiation, the intensity and the persistence of behavior. Nevertheless, students are not always highly motivated. Previous research has claimed that a game's story can motivate students to use an educational game (Bopp, 2007). Within the field of game design, narration is beneficial into a learning environment (Malone 1981, Kelleher et al. 2007) and provides opportunities for reflection, evaluation, illustration, exemplification and inquiry; especially on arithmetical concepts. Thus, our first design pattern is centered 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 highlighted strategies for employing popular commercial games (e.g., Rovio's Angry Birds) in a Physics course (Rodrigues and

Carvalho 2013), but it has not provided any actual implementation of the respective concepts. A common strategy in interaction design has been the use of metaphors from the real world or from similar digital domains. For example, the popular desktop computing paradigm is a metaphor of the working space. Thus, our second design is related with the use of familiar interactions (metaphors) from popular video game formats (e.g., platform games).

Table 1. Design principles for serious video games

Theory	Design Principle	Source
Hero and narrative	Engage students with narrative (hero, story)	Kelleher et al. (2007)
Familiar interactions	Engage students with familiar game mechanics from popular video games	Rieber (1996)
Trial and error	Engage students with constructive gameplay	Gee (2009)

Rieber (1996), Gee (2009) and Dondlinger (2007) have provided a list of generic design principles that has an overlap with those in Table 1 for serious video games, but there has not been any formal application of those principles in the design of a serious video game.

3. GAME DESIGN

We consider that the design of a meaningful game is both art and craft. Although it is difficult to build design theory for the art part, there are some design guidelines with regard to the craft aspect of a video game. Firstly, we consider that the game design space should be mostly motivated by pragmatic need, which is defined by the teacher of a course. 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 course, technology, and students' needs should preferably design a meaningful game.

In this way, we designed and developed a math game in Scratch, with the assistance of mathematics and informatics teachers (figure 1). The video game with the name "Gem-Game" is available for further improvement by the Scratch community (Source Code).

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.

3.1 Hero and Narrative

The 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. According to Vogler (1998) 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 (Figure 2, right). When Peter collected the diamonds, the fairy is appeared, fairy called the witch, witch is appeared and gets the diamonds, release the dog and the moral aspect of the game is presented.

3.2 Familiar Interactions

The gameplay of the Gem Game is inspired by the classic side-scroller video game Scramble by Konami (see Figure 2). We wanted the game on its whole 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. The game is targeted to children that attend first and second grade of Gymnasium (Middle School) (13-14 years old). The main purpose 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 (See figure 4).

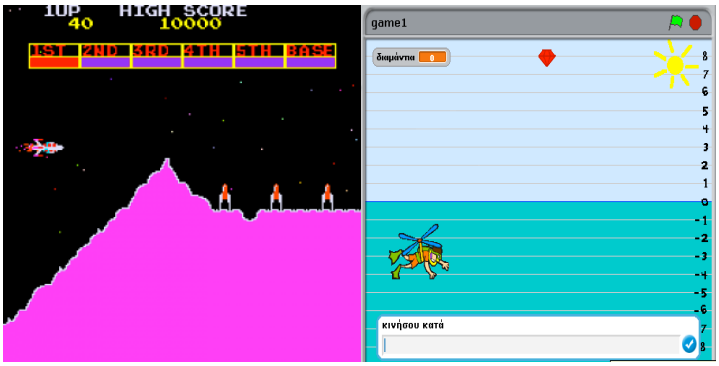

Figure 2. The gameplay of the Gem Game is inspired by the classic side-scroller video game Scramble by Konami.

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.

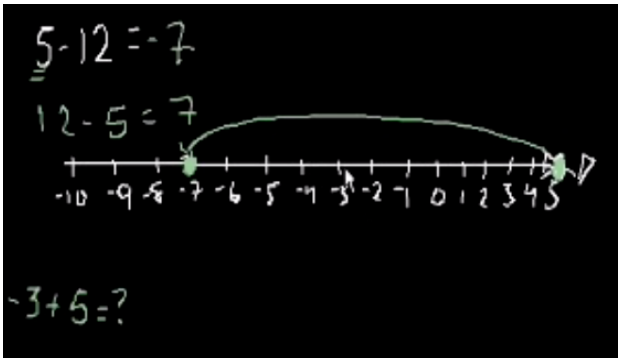

Figure 3. Video lecture on the topic of adding signed numbers employs a spatial representation of the numbers, but it is not interactive.

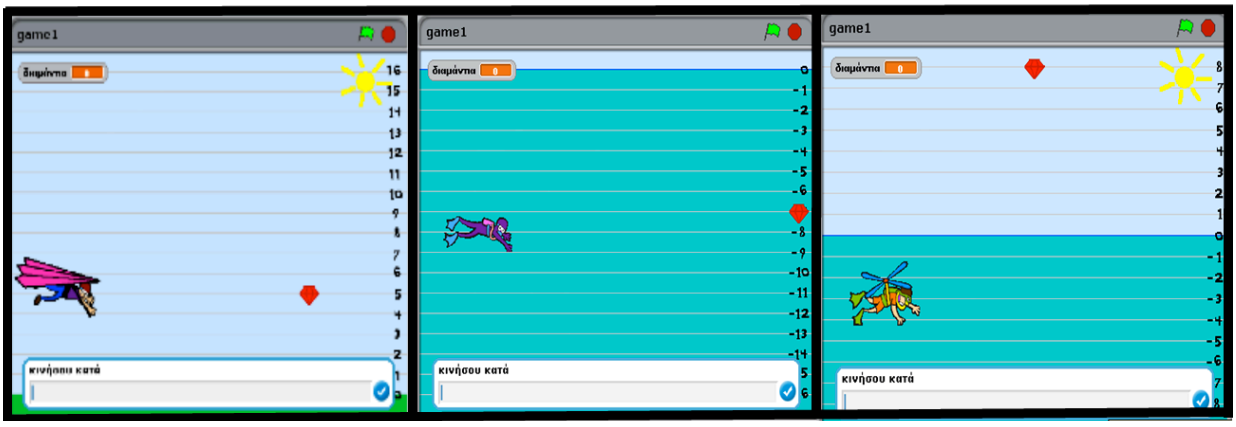

Figure 4. The first stage has only positive integers, the second stage has only negative integers, and the last stage has both positive and negative integers, which are visualized by the respective air, underwater, and amphibious hero outfit.

The main character (Peter) moves up or down dependent on 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 5). The player must go through the three different levels (figure 4). In particular, the player must correctly perform numerical operations (addition – subtraction) 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.

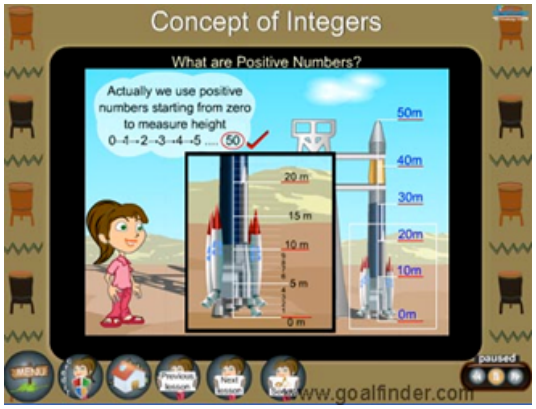

Figure 5. Interactive multimedia on the topic of adding signed numbers employs a spatial representation of the numbers, but it does not employ engaging game mechanics.

The level of difficulty is another important aspect of the game design, for instance when a player fails to pass one game task, his frustration increases as his self-esteem decreases and vice versa (Seery et al., 2004). Therefore, successful task resolution is theorized to level out self-esteem, and the increase of self-esteem is a highly enjoyable experience. Successful task resolution in an educational game means playing at a higher level of the game with more difficult competencies, resulting in better performance for the learner. In addition, the sense of enjoyment while the students learn through a game reduces anxiety and helps students feel confident about their success. We can then assume that higher levels of enjoyment facilitate higher levels of success (better performance).

As aforementioned, the first level has only positive integers, the second level has only negative integers, and the last level has both positive and negative integers. In addition, each stage has different background and the main character wears 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 6), 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.

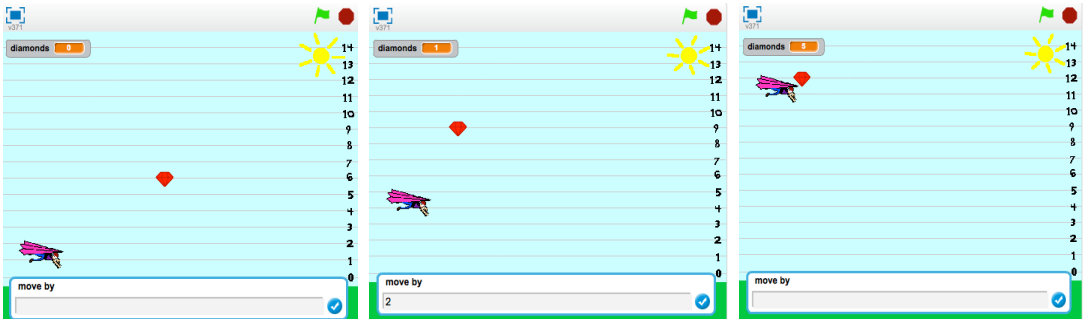

Figure 6. It is possible to provide the right answer by thinking spatially and by trial and error, just by counting the steps required to move from the hero position to the one of the diamond, so if the player makes a mistake, it is a constructive one, because the player can continue by typing a correction from the new position.

4. CONCLUSION

In this work we proposed design principles for enriching serious video games with the appropriate elements and learning practices. The proposed principles are backed by studies mentioned in the literature, hence this provide some assurance of their validity. In particular, after identifying those principles we also applied them in the field of serious video games with illustrated examples.

In addition to the Gem Game, we have also applied the design principles in the development of several more serious games for mathematics (Figure 7). For example, Underwater Math[1] and Math in Space[2] provide the student with a target score, which can be reached by collecting starfish, or stars respectively. Although those serious video games do not include the constructive feedback design principle, both of them include the threat of an enemy: a shark or a meteorite respectively. In future versions of those 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, we are aiming to make the notion of "game over" irrelevant and we are focusing on encouraging the player to make more calculations even if some of them are not correct.

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

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

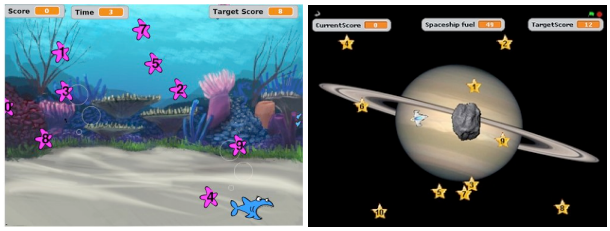

Figure 7 Underwater Math (left) and Math in Space (right) are two more serious games that have been developed by following the design principles

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; humor makes the students attentive and creates a comfortable learning atmosphere (Nordkvelle, Fritze & Haugsbakk, 2009). 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.

Designers, educators, practitioners, and researchers in the area of technology-enhanced learning could employ, revise, and expand the design principles. In addition, they should be also evaluated in order to ensure their validity.

5. ACKNOWLEDGMENTS

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