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Learning Mathematics and Critical Thinking via Computer Games Design

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Abstract: One of the most popular technologies today is computers games often played outside of school. The surge in online resources and communities could transform students into mere consumers of computer games without having opportunities to critically analyze the content of the games and understand their cognitive impact. Research indicates when students are challenged to design their own educational computer games in a classroom setting, they learn significantly more and deeper content—enhancing students' achievement. Designing and creating computer games allows students to understand and learn most challenging mathematics concepts such as rational numbers, functions, and skills required in today's work force. By actively engaging students in "hands-on" activities where technology is used as a means to learn the mathematics, learning can be authentic and 21st century skills can be developed. Taking advantage of students' motivation to play games, a teaching model was implemented in which students design their own educational computer games in order to learn in-depth mathematics content. Feedback from 200 students in a middle school campus serving low SES population revealed (1) With high expectations and thoughtful coaching from the teacher, students can successfully plan, develop and create educational games; each of these phases required students to research information about technology, mathematics and other related subjects, (2) Students' engagement was apparent and sustained throughout the process of game development, (3) Students' social and communication skills were improved through peer tutoring and collaboration, and (4) Game design methodology promotes differentiation based on students' needs, interests and abilities.

Key words: Assessment, critical thinking, computer game design, differentiation, educational computer games, engagement, problem solving, technology.

1. Introduction

"I am planning on having my students work on designing a game for about 3 weeks. Here is my outline/ check points that I am planning on using with the students. What do you think about this? Did I miss any crucial step? Thank you!" (Grade-6 mathematics teacher, a former student in our teacher preparation program for Middle School)

The email message above reveals the enthusiasm of a first-year teacher from our teacher preparation program who has taken a course titled, "Integrating technology in the middle grades: Parts 1 & 2". Middle school mathematics pre-service teachers taking this course feel prepared and motivated to infuse educational computer game design into their own classroom with the intent of helping students learn and interact with the mathematics content. The goal of this teaching approach is not to make students merely consumers of commercial games but to encourage them to design their own, ask questions and research for answers, and to focus more on the process rather than the final product. These experiences will consequently develop critical thinking skills needed in today's workforce.

In our society today, students' interest in technology and its use is phenomenal. One of the most popular technologies is computer games (e.g., video games). Data from *Video Game Industry Statistics* (https://www.coursera.org/course/videogameslearning)

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reported Americans spent about 21 billion dollars on video games in 2012. Students typically spend at least 10 hours a day interacting with different media (games, music, videos, etc.) and only an hour doing homework. In a 2015 statement released by the Bill and Melinda Gates Foundation (http://www.gatesfoundation.org/), it is now typical to see a pre-school child using his/her parents' smart phone to learn numbers, letters and play games—giving the young toddler a significant advantage in learning.

It is also commonplace to see students as mere consumers of computer games which they play outside of the classroom. The widespread use of commercial computer games has its setback; the students (players) do not have opportunities to critically analyze the content of the games and learn how these games are designed. The goal of this paper is to describe classroom tested opportunities for students to design educational computer games and at the same time learn important concepts of mathematics and critical thinking through a basic knowledge of current technology applications. The following questions will be addressed in this paper:

(1) Can educators take advantage of current students' interest in computer games and help students learn meaningful mathematics in middle school mathematic?

(2) How can a teacher incorporate mathematics, critical thinking, and technology into the process of game design?

2. Computer Games and Cognition

Computer games require the player to do something-whether to run, jump, kick, move a square, or aim a target. According to Squire [1], games allow players to learn by doing and performing actions; in a digital world cognition is mediated by players' capacities for action (p. 22). Players must do something in order to participate in the game. The "doing" involves metacognition as the participant is actively, rather than passively, participating in the context. Van Eck [2] further reiterated that games become an effective medium for engaged participation "not because of what they are, but because of what they embody and what learners are doing as they play the game" (p. 18). According to Gee [3], effective video games should be designed so that powerful learning can occur: They must require players to make choices and see immediately the results of these choices. Gee argued "people learn best when they get immediate feedback" (p. 21).

Game based learning allows for content delivery within the game to occur "just in time", as the player needs it [3]. Students can acquire new information in smaller pieces and within a meaningful context. Well-designed video games support in-depth learning and awareness through situated learning in which meanings are constructed from these experiences [1, 3].

3. Research on Game-Based Teaching

A national survey (n = 403,000) by the 2013 *Project Tomorrow Speak Up* [4], reported 25% of the classroom teachers polled were using digital games. Meanwhile, in the middle school, only 21% of the teachers are using digital games. About 32% of elementary teachers who were using digital games in their classroom elaborated their goals for using computer games: (1) to help increase student engagement, (2) differentiate instruction, and (3) accommodate varied learning styles. Moreover, 88% of the teachers who claimed they used computers games in their teaching saw real benefits in terms of high student engagement.

Research further indicates the effectiveness of video computer games on learning and motivation for both students and teacher [5, 6] and improving problem solving [7].

A study by Gillispie, Martin, and Parker [8] sought to measure the impact of using computer games on

students' learning of Pre-Algebra and Algebra concepts. Using an interactive video game called Dimension-M, the researchers examined if the game experience alone could positively affect learning and influence the participant's attitudes towards mathematics. Players navigated through a virtual, maze-like world, encountering barriers removed only by successful completion of an algebra problem. Players received immediate gratification in the form of points awarded for success or a time penalty for failure. The researchers found students made significant gains in their overall academic achievement. However, there was no significant improvement in student attitudes towards mathematics or video games.

Justifications for the use of game design methodology in the classroom along with associated learning theories were discussed by Brown and Koptelov [9]. Some of these include support for inquiry approach, Project-based learning, and constructivist learning. There is also a strong support for game development from the neuroscience research [10] as well as an emerging research on identifying misconceptions in mathematics (e.g., fractions) resulting from students' actions in educational video games [11].

Although the research interest in game-based learning is gaining prominence in the U.S. [12], the research on designing educational computer games by students themselves, is still in its infancy. One such study from the Institute for Research on Learning Technologies [13] utilized game design as a literacy activity.Another study [14] reported success in students with disability in terms of improved communication and social skills.

4. Learning Mathematics and the Common Core States Standards

Critics of mathematics teaching in the U.S. target rote memorization and no in-depth learning taking place in the classroom as serious problems. The lack of motivation and student disengagement is also pervasive in today's classrooms [15].

Meanwhile, the Common Core States Standards (CCSS) for middle school mathematics support a strong focus on developing rational numbers, proportionality, functions, and mathematical processes (e.g., problem solving, use of appropriate tools, attend to precision). These topics are typically perceived by students as insipid and not worth learning. Having negative attitude leads to boredom as students feel powerless and unable to engage in satisfying activities [10, p. 29]. With creativity and access to current technology, middle school mathematics teachers can provide students with meaningful opportunities such as developing models (e.g., scale), applying proportional reasoning, and designing models not only of real world infrastructures but also web-based programs(e.g., computer games). Why not help students learn important mathematics and increase student engagement via game design and development?

5. Software for Designing Educational Games

Due to the high interest in video games by both students and teachers, there has been a significant rise in online resources and communities. The National Council of Teachers of Mathematics has provided guidelines for searching and selecting mathematics video games [16]. It also has recommended areas for further research.

Based on our experience in educational computer game design, we found "Scratch" (http://www.scratch.com) easier to understand and use for developing entry level educational games. It is a program that allows students to design interactive stories, games, and animations. Students can also develop games with others in an online community. "Scratch" developers claim this program can help young people learn to think creatively, reason systematically, and work collaboratively which are

essential skills for life in the 21st century" (http://www.scratch.mit.edu/).

We also began using "Game Studio" (http://www.yoyogames.com) and found it designer-friendly. It offers a free software version that has good tutorials and online resources to help students get started on the development of their own educational games. Most of the time students can work independently and, occasionally, seek instructor's help. In addition, the following tools from www.clickteam.comcan be useful:

- The Game Factory 2—basic level
- Multimedia Fusion 2—more advanced level
- Multimedia Fusion 2 Developer—professional level.

Finally, the program named "Game Salad" (www.gamesalad.com) is another option for teachers' and students' projects. It does not require coding and students learn how to think like a programmer while creating their own educational games. This software allows the designer to create games for different platforms including mobile devices like a cell phone.

6. Stages in Educational Computer Game Design

Our teaching approach to game designing integrates at least three basic stages. First, planning and designing an educational computer game based on educational objectives. Second, creating (visual programming) the computer game. And lastly, testing and playing the game to assess basic concepts or learn specific objectives in mathematics. It becomes even more interesting if there are some elements of competitions embedded in the game design. Most importantly, meaningful learning needs to occur as the learner interacts with the computer games.

In the following section we describe nine sequential and logical steps we followed as we helped our students develop their own educational mathematics games.

(1) Identifying educational objectives (based on math standards) and the appropriate type of game to meet the goal. For example, the game can be used for delivering new instruction, reviewing mathematical content or for post assessment. In this stage, the students may have to research about several options and types of games.

(2) Analyzing and decomposing different types of computer games based on research by students or given by a teacher. At this stage students analyze goals, objectives, and events of their game. They are getting close to putting their ideas in action, creating their own game using analytical and critical thinking.

(3) Creating and discussing student's own ideas of the game using critical and abstract thinking, creativity, and imagination.

(4) Deciding how educational components will be integrated into the overall game concept and game mechanics (e.g., movement, speed, design). This is one of the most important steps if the game has to involve learning of mathematics concepts. Students must use their knowledge of mathematical objectives and think creatively. It is important to choose and embed complex and challenging problems in order for students to apply in-depth content.

(5) Designing, selecting, and editing new characters (called sprites) and environments of their own game using graphic, sound, and other editors. Students necessarily use decision making, critical thinking, and creativity during this phase.

(6) Analyzing and designing events, actions, and levels of the game. These tasks help form and develop students' analytical and critical thinking, and apply their knowledge of mathematics (e.g. algebra) as a tool especially when they work with variables.

(7) Synchronizing different actions and proper interactions between objects. Students have to analyze and review how players and game characters will interact and how mathematical content will be represented in this interaction. The designer makes all necessary corrections

and modifications. They need to apply critical thinking and mathematics content and skills.

(8) Testing to further improve the game; including creating and organizing new levels, savers, scores, backgrounds, and sounds. Students continue learning and analyzing the content of the game and apply creativity, critical, and mathematical thinking.

(9) Sharing the game with peers for feedback and analyzing quality of the game.

7. Sample of an Educational Game Designed by a Student

Figures 1 through 3 show screen shots of a game designed by a middle school student (Grade 6) using the free program version of "Game Studio". The goal of this specific game is to help students understand and recall basic concepts of square roots.

Figure 1 shows a student-designed page which includes instructions how to play the game and earn incentive points.

In Figure 2, the same student designed a maze to find the way to the next level (on the screen it represents as a gate or door), but the path is blocked and can be cleared only by opening several treasure chests after giving correct answers to given questions about square roots. Choosing correct responses will allow the player to move forward and gain points. When a wrong answer is given, points will be deducted and the player cannot continue until a correct answer will be given. Different comments are provided depending on the student's responses. This design is similar to the game used and described by Gillispie, Martin, and Parker [8].

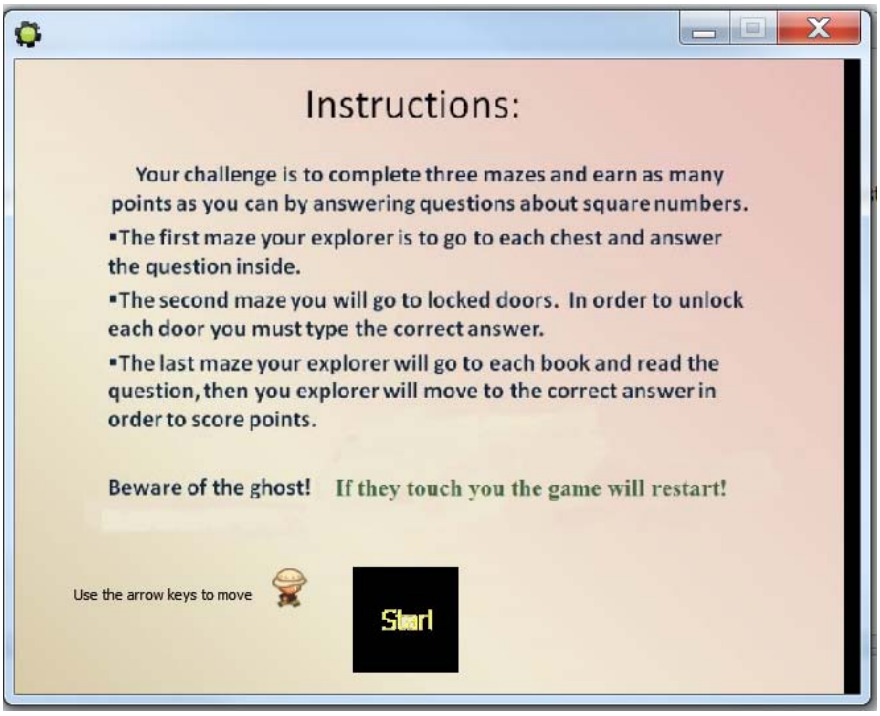

Fig. 1 Screen shot showing directions to play the game.

Fig. 2 A screen shot of a maze designed by a student.

Execute Code

Applies To: Sel Othe Objec Chest1

```
1  corr_answer='9';
2  answer = get_string("What is the square root of 81?",'');
3  if(corr_answer == answer)
4  {
5     show_message("You are correct!! Proceed!!");
6     score += 5;
7     with (Chest1)
8     {
9       instance_destroy();
10    }
11 }
12 else
13 {
14    show_message("That answer is INCORRECT. Please try again.");
15 }
```

Fig. 3 A sample of a student's coding system for the maze game.

The game designer may change/modify the question or the topic by editing the content of the code. An example of a coding system is shown in Figure 3. The editable questions, answers, and scores are shown in blue font. The student designer becomes a "script writer" with the ability to anticipate "correct" or "incorrect" responses and provided appropriate feedback to the player.

8. Impact on one Middle School Campus serving Low SES Students

In this section we will report preliminary data collected on 200 middle school students all of whom were taught by the first author who implemented game design in his technology applications class. Most of his students decided to design games that assess mathematics or science content knowledge. The students used these games to show evidence of their learning of different grade level mathematics standards. Hence, the teacher was using these educational games as a performance based assessment. Additionally, the students were gaining both communication and collaborative skills.

Students' feedback from a middle school class provided us with valuable insights into this type of teaching practice. We have learned that engaging students in developing content-based computer games enhances motivation and interest in mathematics and other core subjects' areas. The activities that were conducted in multiple phases supported critical thinking and sustained students' interest in exploring and learning more. Playing educational games created by students themselves seemed to sustain their interest, curiosity, and motivation throughout the process.

With high expectations and proper coaching from the teacher, students can successfully plan, develop and create educational games and conduct necessary research to complete their educational computer game development projects. Students can complete different parts of the project independently either individually or in groups. They did not hesitate to ask for help and seemed involved in the process.

The following are added reflections based on our evaluation of students' process and outcomes (educational computer games):

(1) By working in groups, students developed strong communication skills, learned how to find information about math and technology, and helped improve their social skills through a collaborative work;

(2) Working in pairs and in groups supported positive relationships by using peer teaching and cross age tutoring;

(3) The process of creating educational games provided a good opportunity for differentiation according to students' interest, knowledge and abilities;

(4) Students found/identified their strengths and areas for improvement;

(5) At-risk students and students with learning disabilities made adjustments and still met basic and even advanced mathematics objectives as well as technology in their own unique ways.

9. Feedback from Middle School Students

Written feedback from our sample included the following when they were asked how educational computer games have benefitted them:

(1) It was fun;

(2) Held students attention;

(3) Made studying easier;

(4) Helped with foreign language content;

(5) Helped with mathematics content;

(6) Desire to win the game made me work harder;

(7) I did not realize I was studying.

Students also explained why commercial computer games did not help them to learn the content. Typical responses included: Not my learning style; Pointless lessons/boring games; Games, not educationally organized; Games were not personal to the students.

10. Implications and Recommendations

The 21st century learners are sitting in our classrooms ready to explore, design, and create models using elaborate cognitive processes like critical thinking. School leaders and educators need to provide the needed resources for effective technology integration. Using technology as a powerful and exciting educational tool allows students to problem solve, think critically, collaborate, and encourages student creativity and motivation while learning.

The negative feedback from middle school students about commercial games indicates private companies develop computer games without considering students' learning styles, differentiation, and learning strategies. This problem can be solved if teachers and students will become involved in the designing and developing computer games for learning according to their interests and specific needs. Our computer game design approach promotes students' interest in mathematics and technology by uniquely scaffolding the content delivery, making the mathematics more understandable and exciting for the students.

The potential benefits associated with game design seem boundless. Students write story lines, edit pictures, use logical reasoning, experiment with sounds/amplitude, and learn the trade of graphic design. At the same time, students are interacting with rather complex concepts in mathematics. Students learn mathematics and modern technology that can transform them into a world of creating/designing which can boost students' interest in the areas of science, technology, engineering, and mathematics (STEM) [17].

Implementing educational computer games design in the mathematics classroom can support student success on the coming CCSS assessment developed in 2014 by the Partnership for Assessment of Readiness for College and Careers (PARCC) that measures application of mathematical concepts through problem solving and reasoning, rather than on memorization of information [18]. Students' affinity and fascination with technological tools could be a viable means to help students meet the CCSS mathematics standards through innovative game-based pedagogy. By actively engaging the students in 'hands-on' activities where technology is a means to learn the mathematics, learning becomes authentic and students are inclined to use critical thinking.

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