THE PAST, PRESENT AND FUTURE OF SERIOUS GAMES AND GAMIFICATION IN STEM LEARNING

Pedro A. Santos
Departamento de Matemática /INESC-ID, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal

Abstract. *I present here a short personal position paper on the role of serious games and gamification in school children STEM learning. I argue that the technology is ripe and there is a strong theoretical foundation on Game Design, but still there is a lack of good games or gamified activities that can show the potential of this novel learning tool. I have been designing or collaborating in the design of games for many years, both boardgames and videogames, both serious and non-serious, and have implemented gamified classroom approaches.*

Key words: Education, Learning, Serious Games, Gamification.

INTRODUCTION

Serious games have a long history. Mammals are biologically primed to use play as a learning and training tool. One has just to look to a dog or cat playing with an inanimate object like a ball or small rock to understand this. The potential of directing children's playfulness to serious purposes was recognized already in ancient Greece, as attests the following passage by Plato (D'Angour, 2013):

"*For example, if a boy is to be a good farmer or a good builder, he should play at building toy houses or at farming and be provided by his tutor with miniature tools modeled on real ones. ... One should see games as a means of directing children's tastes and inclinations to the role they will fulfill as adults*"

Clark Abt coined the term "serious game" with its current meaning in 1970 (Abt, 1970). A century earlier, the first highly visible serious games were simulations of land battles for the training of military officers. But while the Prussian Officer Corps were playing *Kriegspiel*, at the same time other young adults were learning how to do fireworks on their own and in the process being inspired by Chemistry.

STEM AND PLAY: LOOKING INTO THE PAST AND PRESENT

While the connection between play and learning was made since antiquity, one would have to wait until the industrial revolution for the society to give importance to STEM education, in the Darwinist nation on nation competition that characterized the later part of the nineteen century.

STEM Toys

Industrial production of STEM toys started with the interest in Chemistry and Mechanics in the 1800s (Nicholls, 2007). The first Chemistry sets for children appeared in the 1830s. In 1901 Frank Hornby patented a toy based on the principles of mechanical engineering called "Mechanics Made Easy" that was to become the *Meccano* line of construction toys. Whole generations of future engineers were inspired by playing with these toys. But to my

Santos, P. A. (2020). The Past, Present and Future of Serious Games and Gamification in STEM Learning. In M. Ludwig, S. Jablonski, A. Caldeira, & A. Moura (Eds.), *Research on Outdoor STEM Education in the digiTal Age. Proceedings of the ROSETA Online Conference in June 2020* (pp. 147-154). Münster: WTM. https://doi.org/10.37626/GA9783959871440.0.18

dismay, more than one century later when I tried to buy a Chemistry Set for my daughters, I could not.

My first memories of the power of STEM learning via play come from my childhood, when a small Electricity playset with lamps, switches and buzzer made me understand how electricity worked. As a pre-teenager a few years later, a Chemistry set (see Figure 1) made me understand the basics of chemistry. At ten years old, it was a revelation to me the table sea salt was just a simple chemical compound with the esoteric name sodium chloride that you could actually manufacture. I started to connect STEM knowledge with everyday life. Science could explain the whole world!

Figure 1: The Chemistry Set from my youth; you cannot find them in stores anymore...

Another couple of years later I understood the principle of a gearbox and how a driving wheel turns the front wheels of a car by assembling a complex LEGO set. Cogwheels were really interesting. If you connected a cogwheel with another one with double the cogs, one would rotate at double speed of the other. Building a chain of interlocking cogwheels, this process could be repeated. So I imagined I could build a bicycle that would run at incredible speeds. Trying to build such a mechanism using LEGO pieces, showed me first-hand the trade-offs involved.

What those sets gave me was much more then I could get from a book. By physically manipulating, working and experimenting with chemical compounds, electrical components and cogwheels I was getting insights that no other medium could give me at the time. And Mathematics was the language that could describe many of the things that I was experiencing[1].

[1] The math I was learning at school did not make that connection, though.

Unfortunately it seems that safety concerns and consumer regulation got the better out of children STEM education, by removing the most interesting experiments and components from chemistry and science sets (it might be argued that sets like the 1950's Gilbert U-238 Atomic Energy Laboratory were in fact a bit over-the-top)[2]. These types of toys also appeal to more self-motivated children, who are comfortable with setting their own goals.

While there was a decline in the attractiveness of traditional chemistry and electricity/electronics sets, a new generation of STEM toys appeared in the 1990's, mixing the mechanic parts of the build set toys like LEGO's Technic line and Meccano with programming. These are of course the Robotics sets such as the Mindstorms line from LEGO and the Meccanoid Robot-Building Kits from Meccano, which for twenty years now have brought many kids and teenagers to interact with very good STEM toys.

STEM Games

One moves from playing with toys to playing games by the introduction of arbitrary (i.e. not prescribed by the environment or physical properties of the artifact) rules and the acceptance of specific goals in an activity (Santos, 2008). Compared to STEM toys, both physical and video STEM games are a relatively recent phenomenon (with the exception of John Spinello's *Operation* published by Milton Bradley in 1965). In terms of physical (board) games, most STEM games on the market are of the puzzle genre, for instance marble or domino runs: *Gravitax* (2018) from Ravensburger, *Gravity Maze* (2014) and *Domino Maze* (2019) from Thinkfun.

Taking into account that one of the most famous boardgames in history – Monopoly – started its existence as a serious game[3], it is maybe disheartening to verify that very few STEM boardgames exist. A notable exception is John Coveyou's *Cytosis* (2017) published by Genius Games, where the players use a worker placement mechanic to simulate a human cell's metabolism.

STEM videogames

The potential application of videogames for serious purposes was perceived almost immediately (Wilkinson, 2016). But videogames were understood by the generation that grew up in the 1970s and 1980s, playing in the arcades and programming their own games. For their educators and political decisors, videogames were violent and addictive, a menace to society. It was necessary to wait for the 1990s for both a generational shift and the ubiquity of videogames to clear the way for the widespread acceptance of videogames as a learning tool.

Djaouti et al (2011) counted 2218 Serious Games launched until 2009. Of the 1265 games launched from 2002 to 2009, about a quarter were classified in the "Education" category. But how much good STEM games were produced? Not many, unfortunately. As several authors mention at the time most earlier educational games were *"Shavian reversals":*

---

[2] I did continue devising my own experiments, for instance playing with fire or trying to build small solid propellant (home-made powder) rockets at age thirteen (would that be considered an outdoor STEM activity nowadays?).

[3] The Landlord's game, patented by Elizabeth J. Magie in 1904, see the interesting account in Adams, C.J. (1978)

offspring that inherit the worst characteristics of both parents (in this case, boring games and drill-and-kill learning) (Papert, 1988 and Van Eck, 2006).

The situation seems to have improved somewhat in the last decade (Chen, 2016). Some Serious Game designers, while still not having the resources lavished on AAA entertainment titles, started to develop games applying the concept of "Stealth Learning", where learning is happening implicitly while the player is having fun with the game. Also, they use game design techniques and ideas common with entertainment games. For instance, in the NASA-published *Moon Base Alpha* (2010)[4], players play as astronauts and are put in a typical videogame situation: a meteor strike damages the outpost, gamers are tasked with repairing vital systems using a variety of tools, from the lunar rover to remote-controlled robotic units. But the game uses actual NASA Constellation program design details developed by NASA for mankind's return to the Moon, with immersive 3D graphics.

The mobile game *Math Evolve* (2011) from InterAction Education is also an interesting example of good educational game design. It teaches the basic math operations, but contrarily to the (in)famous *Math Blaster* Series (1983-2013), where the math content interrupts the normal shooter gameplay of the game, in Math Evolve the math content is tightly integrated with the gameplay.

A third example of this new generation of games is *Kerbal Space Program* (2015)[5] from Squad. The basic gameplay is assembling rockets from parts and attempting to explore a solar system. The point is that the laws of physics are realistic (at least equivalent to the models actually used by scientists and engineers in the 1960s). The player will fail a lot, but failures are fun and make the player learn and try other approach. The game includes intelligently designed interfaces that make it easier to understand what will happen with the player decisions and space maneuvers (that must be performed manually). It is surprising how even 8 years old children can learn very complex aeronautics and space exploration concepts like thrust to weight ratios or orbital mechanics with this game. And they do learn all of these while having a lot of fun!

Lastly, I will mention a project I was personally involved, the game Treme-Treme (2015)[6]. It is a game designed to teach 9 to 12-year-old children what to do in case there is an earthquake. The game had three chapters (before, during and after the earthquake, each with its own mechanics) For the design of the gameplay during the earthquake, the idea was for the child to know where it was safe and not safe to stay, and what to do in the moments immediately after an earthquake (if possible switch of electricity and other utilities, pick the emergency kit and leave the house). I took inspiration from two entertainment games, not usually associated with that age bracket: *Dark Souls* (2011) and *Limbo* (2010). From *Dark Souls* I took the concept that you learn by failing and dying, and quickly trying again. From *Limbo* I took the idea that if you are going to die a lot, then one should make it interesting.

[4] https://sservi.nasa.gov/articles/moonbase-alpha/

[5] https://www.kerbalspaceprogram.com/

[6] https://www.treme-treme.pt/

Figure 2: Gameplay screenshot from the game Treme-Treme (2015).

The gameplay in that part of the game is very simple (see Figure 2): The player has side view of the interior of the house and moves by clicking where he wants to go. We do not say where the safe places are. He starts in a random division and has 10 seconds to choose a place and get there. After those 10 seconds, if he is not on a safe place (e.g. under a table or bed), something will happen (a lamp falls on his head, the balcony falls, and so on) and he dies. A small angel gets out of his body and flies up, while a short text explains why that place is dangerous. Then that level starts again. We have observed that the children try several times different places and, in the end, learn **by experience** the places where it is safe to be. And they have fun!

STEM learning with Gamification

The most common accepted definition of Gamification is that gamification is the act of using game design elements in non-game activities to make them more enjoyable (Deterding et al, 2011). While gamification is often equated with the use of badges and rankings or the enveloping of activities within a narrative, it is possible to re-design activities and the learning process to incorporate game design principles and gameplay mechanics, thus attaining a deeper level of gamification (Santos, 2015).

Gamification works, at least in my experience. If implemented properly, it changes student attitudes, increases motivation and creates an environment where failure is seen as a step towards success. Unfortunately, there is still a lack of academic studies to formally analyze its effects in controlled tests. In the MoMaTrE[7] project we have implemented and tested a gamified version of the system versus a non-gamified version, with positive results (Gurjanow et al, 2019). We have continued to develop gamified aspects of the application,

[7] http://momatre.eu/

like introducing the possibility of adding a fictional narrative to envelop the student activities. Unfortunately, the Covid 19 situation let to the cancellation or postponement of studies that were planned to test its effects.

In fact, in what regards the effects of STEM games and Gamification, there is still a dearth of information and studies. While some studies show in fact that there is no effect in the use of interactive material compared with alternative methods (workbooks) in student performance (e.g. Reinhold, 2019), other studies show statistically significant improvements with the use of STEM games in schools (e.g. Freina et al, 2018).

More studies to shed light on this and related subjects are sorely needed. A large-scale study involving the MoMaTrE project results and the MathCityMap App is planned to start in the next school year (Barlovits and Ludwig, 2020). Hopefully, it will bring interesting results.

STEM AND GAMES: A BRIGHT FUTURE?

As we have seen by the examples above, in the last decade there has been a trend where new STEM serious games were developed considering modern game design principles, where the learning component is tightly integrated with the gameplay. So, in a certain way, for the player, he is playing the game just for fun and learning occurs naturally. Of course, designing serious games using this design philosophy is harder than designing pure entertainment games or the more traditional Edutaiment type games. The designer must design the gameplay to be both fun and to teach the player the knowledge that was the purpose of the game, thus provoking stealth learning.

It does not help that funding for the development of STEM games is usually very restricted. Entertainment games publishers avoid serious games, because they think it is harder to have success, and so the development of Serious Games is usually done by small companies with little resources, doing many times work-for-hire. But while there are companies that have interest in financing advergames , who is interested in financing STEM games? I think that here state education systems and other stakeholders should have an active role in this process.

Technological evolution is also presenting new opportunities and risks. New XR – technologies, that is, virtual reality and augmented reality technologies, are becoming common and open a new frontier for STEM applications. What is too dangerous or expensive for children and teenagers to do in real life (manipulating dangerous chemicals, working with lab equipment) can now be simulated in immersive environments. But not only that, VR opens a whole new world where we can experience things and make activities which are impossible in “real life”, all in a safe environment for experimentation. There are already experimental games and interactive experiences that allow one to grab atoms and play with them (Rodrigues and Prada, 2018). One can also replicate what I experienced as a teenager manipulating LEGOs, but now on a real-life scale: it is possible to show how any machine works inside, while letting the student manipulate and observe everything from different angles. It is possible to virtually disassemble any machine, to be inside a working engine, or the human body.

The imagination is the limit. I can only advise all educators to try XR technology to understand its potential for education in general, and STEM education in particular. Any description or video does not make it justice, one needs to experience it.

CONCLUSIONS

STEM games are fundamental if we want the current generation of computational native children to learn and have interest in STEM, together with developing problem solving and critical thinking skills. Of all the new technologies that appeared in the last years, I think XR technology is the most promising to bring a revolution in STEM serious games.

I will finish with a few pieces of advice for the design of new STEM games that enhance student learning:

- Design for Fun, and integrate learning in the core gameplay loops;
- Heed the teachings of the wise (game design) men;
- Consider both shallow and deep gamification techniques;
- Harness the potential of new technology.

I believe that if one follows these simple four lines of advice, together with some financial support for this important aspect of education, there will be indeed a bright future for STEM Game-based learning.

References

Abt, C.C. (1987). *Serious Games*. University Press of America

Adams, C.J. (1978). MONOPOLY: From Berks to Boardwalk. Historical Review of Berks County, Vol XLIV, Number 1 Winter, 1978-1979

Barlovits, S. & Ludwig, M. (2020). Mobile-supported Outdoor Learning in Math Class: Draft of an Efficacy Study about the MathCityMap App. Proceedings of Roseta Conference 2020 (in press).

Chen, S. (2016). Facing Edutainment's Dark Legacy, http://www.gamesandlearning.org/2016/01/25/facing-edutainments-dark-legacy/.

D'Angour, A. (2013). Plato and Play: Taking Education Seriously in Ancient Greece. Am. J. Play. 5, 293–307.

Deterding, S., Dixon, D., Khaled, R., & Nacke, L. (2011). From game design elements to gamefulness: defining "gamification". Proceedings of the MindTrek '11. doi:10.1145/2181037.2181040

Djaouti, D., Alvarez, J., Jessel, J., Rampnoux, O. (2011). Origins of Serious Games. Serious Games Edutainment Appl. 25–43.

Freina, L., & Bottino, R. (2018). Visuospatial Abilities Training with Digital Games in a Primary School. International Journal of Serious Games, 5(3), 23 - 35.

Gurjanow, I., Olivera, M., Zender, J., Santos, P., & Ludwig, M. (2019). Mathematics Trails: Shallow and Deep Gamification. International Journal of Serious Games, pp. 65-79.

Nicholls, H. (2007). The chemistry set generation. Royal Society of Chemistry. Retrieved 28 March 2020, https://www.chemistryworld.com/features/the-chemistry-set-generation/3004820.article

Papert, S. (1988). Does easy do it? Children, games, and learning. Game Dev. Mag.

Reinhold, F. (2019). Wirksamkeit von Tablet-PCs bei der Entwicklung des Bruchzahlbegriffs aus mathematikdidaktischer und psychologischer Perspektive [Effectiveness of tablets in the development of the fractional number concept]. Wiesbaden: Springer Spektrum.

Rodrigues, I., Prada, R. (2018). Virtual Reality Game to teach Organic Chemistry, In Proceedings of Videojogos 2018.

Santos, P.A. (2008) Games - Refining the model. In Proceedings of Digital Games 2008, 6-7 Nov 2008, Porto, Portugal

Santos, P.A. (2015) Deep Gamification of a University Course, in Proceedings of SciTecIN'15 Sciences and Technologies of Interaction, Coimbra, Nov. 2015

Van Eck, R. (2006). Digital Game-Based Learning: It's Not Just the Digital Natives Who Are Restless. Educ. Rev. 41, 16–30.

Wilkinson, P. (2016). A Brief History of Serious Games. In *Entertain Comput Serious Games LNCS 9970,* 17–41.