CHAPTER 1

Science, Technology, Engineering, and Mathematics (STEM)

Using Games to Teach, Practice, and Encourage Interest in STEM Subjects

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Key Summary Points

1. Many games purport to teach, practice, or encourage interest in STEM subjects; however, many fail to do so in ways that can be statistically shown to be effective. The potential benefits of such games are often overstated. All parties should be more cognizant of realistically achievable outcomes.

2. Designers and educators should establish parameters to determine what constitutes a successful game experience and design usability tests that measure the degree of improvement in students' aptitude and performance following engagement with STEM games.

3. Progress is being made both in building STEM games and assessing their effects. Analysis of some successful games is helpful in determining how to include games in curricula and demonstrating how they support educational goals.

Key Terms

STEM
Self-efficacy
Technological literacy
Scientific method
Intrinsically motivating
Game physics
Playful learning

Introduction

Educators, politicians, and businesspeople are among the many parties concerned about the decline of STEM (science, technology, engineering, and mathematics) competency in the United States. Other countries such as China and the Nordic countries are doing a much better job of preparing citizens for a highly technological and scientifically complex world (OECD, 2013). A scientifically informed and competent workforce is essential for success in an increasingly technological world. Regardless of what kinds of work students eventually go into, understanding the scientific process, fostering a sense of wonder about the world around us and the bodies we inhabit, and encouraging engagement with math and computer programming will enrich their lives and help them make informed decisions as an electorate.

Concurrently, we have seen enormous growth and development in the computer, mobile and casual game markets, along with hardware development that has enabled a range of new ways to interface with computer games on multiple platforms. As a result, academics, funding organizations, and developers have fostered interest in the potential use of games on multiple platforms to help encourage, teach, and practice STEM competencies. Many games, such as *MathBlaster*, which claim to accomplish these goals have been produced and successfully marketed despite the fact that there is little proof of their effectiveness (Greer, 2013). Games that have actually demonstrated measurable success (e.g., *Wuzzit Trouble* in improving math understanding (Beveridge, 2013)) are rarer.

One reason for the difficulty in suggesting that games are more effective at motivating and teaching students than traditional methods is that STEM subjects are complex and difficult, and achieving competency in these areas typically requires long periods of focused practice. Games can be very helpful in exposing children to scientific concepts and demonstrating how fascinating they are, but creating games that successfully teach how to calculate statistics or the properties of different chemical reactions, for example, has proven to be much more challenging. Progress is being made as developers and researchers determine what works best and how to deploy such games in educational environments (Clark, Tanner-Smith, Killingsworth, & Bellamy, 2013).

The profitability of the game industry over the past decade has led to innovation and rapid development of large-scale world simulations, such as *World of Warcraft* and *Eve Online*, which are populated by millions of players. At the moment, these environments are used primarily for entertainment purposes; however, they are now being explored for their educational potential as well. Such worlds can allow students to virtually experience and inhabit worlds different from the one in which they live. For example, researchers at San Francisco State University have created a game entitled *World of Balance* where players can manipulate the presence and growth of the flora and fauna native to a habitat and attempt to organize multiple interacting ecological systems to increase the health of the biome (http://smurf.sfsu.edu/~debugger/wb/). Games such as these demonstrate how complex systems are structured by allowing students to see and change them. Massively multiplayer online (MMOs) worlds can also expose students to economic principles such as currency and exchange rates, or the way incremental increases in technology can favor one side over another in a conflict, and the importance of forming and maintaining alliances. Games can also reduce the tedium of practice by creating environments with achievable goals and intrinsic rewards so that students will be motivated to continue seeking to overcome challenges.

It is important that both developers and educators realistically assess both the potential and limitations of such games so that they can be usefully deployed in learning environments. For example, 3D game environments are much costlier than simpler 2D games with less complex graphics, and are not necessarily more effective at communicating STEM concepts. The previously mentioned game *Math Blaster* allows the players to navigate 3D environments, but the 2D *Wuzzit Trouble* game does a better job of teaching math. New tools are being developed to help educators assess different games to determine what works best in any given environment. Common Sense Media created an online tool (http://www.commonsensemedia.org/app-reviews) where teachers and parents can share their experiences with and assessments of new applications and educational products. Serious game conferences, such as the Serious Play conference, now routinely include panels on outcomes measurement and assessment. The National Science Foundation (NSF) created a track specifically to fund educational STEM games, and academics and game developers are establishing more rigorous standards for demonstrating efficacy.

Students often avoid STEM subjects because they are difficult. Learning calculus and physics, for example, requires complex thinking, hours of repeated practice, and self-discipline. Games may be an important impetus for exposing students to practical uses of STEM and fostering an interest in being able to do it themselves. Simply playing with technology and managing the interfaces through which it is accessed is not enough, however. This chapter seeks to explore how games can be used to help students really go “under the hood” and understand how technology and science operate at a much more fundamental level. Some games create environments that allow players to see and manipulate items, such as molecules, which are very small in the real world so that students can learn how the building blocks of life combine. Other games provide players with actual blocks and give them a sandbox in which to use them to create any kind of structure with a variety of materials. Another strategy is to create a series of scenarios that present the player with complex problems and provide the tools to solve them. The player is given a goal and encouraged to explore.

Academics in the developing field of game studies are working to determine whether STEM-related games actually succeed in helping students engage with and succeed in STEM subjects when they are not playing. This chapter will discuss examples of games that are currently being used successfully to promote scientific thinking and practice. Additionally, we will explore some of the challenges of building such games and list best practices for ways that educators can deploy such games and monitor results.

Key Frameworks

The act of playing games on machines is in and of itself practice with technology (Bertozzi & Lee, 2007). Many intelligent living beings use play as a way to become familiar with and adept at manipulating the tools required for success in specific ecosystems (Heinrich, 1999). Human beings living in technologically complex worlds have an advantage if they have acquired the high-level skills necessary to create and manipulate the technologies that make our world work. Students who play a lot of games on computers, tablets, and phones may experience pleasure from this activity. If the pleasure is interrupted, they are strongly motivated to return to it. Thus, such children are more likely to learn how the technology works so that they can fix it if it is broken and therefore have a better understanding of how it works. The V-chip, which was meant to protect children from adult content, is an excellent example. Many parents were unable to make it work by themselves and had to call their children to figure out how to use and remove it because the children understood the control system better than the parents did (Hazlett, 2004).

Children who play video games are much more likely to want to learn software engineering and computer programming than children who do not (Egenfeldt-Nielsen, 2006; Overmars, 2004). The recent creation and expansion of game design and development programs on college campuses is an international phenomenon that both recognizes the economic importance of the business of selling games (and thus the flourishing job market for developers) and the presence of strongly motivated students who want to be able to earn a living creating a medium that they love.

Researchers have determined that playing science-based games (forensic science mystery solving, for example) both increases fact retention and the likelihood that students will report motivation to pursue science-based careers (Miller, Chang, Wang, Beier, & Klisch, 2011). More longitudinal studies will be required to see if players actually do pursue such careers. Klopfer (2008) has worked extensively on integrating mobile technologies such as phones and tablets into science education by putting students in environments and asking them to solve problems using participatory simulations and play (Klopfer, 2008). Like the forensic science game mentioned above, the idea is to make the learning of science more similar to the practice of science (Rosenbaum, Klopfer, & Perry, 2007). Now that the viability of science games is better established, more specific studies seek to determine which deployments of games are more effective. For example, one study tested to see if is it better to let students play games freely or interrupt the play experience to introduce traditional learning experiences and found no difference in learning outcomes between the two methods (Koops & Hoevenaar, 2013). Other studies are focused on isolating which elements of gameplay are most important to successful learning outcomes. Pavlas et al., found that video game self-efficacy (experience with and comfort level with games as a technology) and achieving a state of flow were the most significant predictors of learning success (Pavlas, Heyne, Bedwell, Lazzara, & Salas, 2010).

Good educational games tend to rest on similar frameworks. Norman (1994), defined some useful parameters for relaying information through games. Games meant to teach should:

1. **Provide a high intensity of interaction and feedback:** As mentioned above, games need to be fun and immersive so that students are engaged and receptive to learning.
2. **Have specific goals and established procedures:** Narrowly-focused games with specific outcomes (as discussed in the case studies) allow educators to assess how gameplay impacts knowledge retention.
3. **Motivate:** Good games have in-game incentives such as scores, badges, leveling up and rewards for victors.
4. **Challenge:** Provide a continual feeling of challenge that is neither so difficult as to create a sense of hopelessness and frustration, nor so easy as to produce boredom.
5. **Direct engagement:** Provide a sense of direct engagement, producing the feeling of directly experiencing the environment, directly working on the task.

There have been shifts in frameworks as more research is done in the field. In the past, games were implemented in the classroom with an “instructionist” perspective (making instructional materials looks like games). A more successful strategy appears to be a constructionist perspective (making games that embed learning) (Kafai, 2006). Early games for learning often seemed merely to be quizzes or flashcards that had been made digital and interactive, but lacked intrinsic motivation (they were not fun in and of themselves). Now it is understood that games have to be fun to play in addition to implementing their educational goals.

Case Study: Crowdsourcing Science (*Foldit* and *EyeWire*)

An important development is the creation and use of games that crowdsource tasks and problem solving. Such games not only help researchers advance their goals, but also allow the general public to view, educate themselves about and play with complex physical phenomenon that they would otherwise be unlikely to be involved with (Good & Su, 2011).

For example, *Foldit* was created because scientists had been unable to resolve certain biomechanical functions without an understanding of how complex proteins were folded. A group of researchers at the University of Washington decided to use crowdsourcing as a way of addressing the problem (Game Science at University of Washington & University of Washington Department of Biochemistry, 2012). They created a series of game environments, allowed anyone to log into the system, and gave players the proteins as puzzles to solve. The environment was competitive and rewarded players both through scoring and through the good feeling that they were helping researchers solve important problems related to human health.

Eyewire (eyewire.org) is another example of making science problems available to the general public. The goal of Eyewire is to map the neurons in the human retina. The game takes a large number of high-resolution images of the brain and asks players to help identify which structures in the images are neurons and which are not. Players are initially trained in this identification through a tutorial and then encouraged to compete with other players to see how quickly and accurately they can identify the greatest number of neurons. As with the *Foldit* game, *Eyewire* allows access to highly detailed and specific scientific information to anyone who wants to login. The images are aesthetically interesting and the challenge is intellectually satisfying.

Both of these games could be used in school environments to show students the complex and fascinating structures that make up the human body and to provide contemporary examples of the ways that science can manipulate them to improve health. Given their narrow focus, clearly defined tasks, demonstrably successful motivational incentives and explicit parameters for success, they serve as examples of the aforementioned attributes of successful educational games. Additionally, the games demonstrate how much time and painstaking attention to detail are necessary to make significant discoveries. Games of this type are not appropriate for all age levels, but they can serve as examples of how complex scientific information can be presented and explained to the public through play. It is important that educational games both demonstrate the potential of science and how difficult (and satisfying) it can be to make progress. Recent studies of the effects of playing these and similar games demonstrate that they do in fact improve cognition (Latham, Patston, & Tippett, 2013).

Key Findings

Although a great deal more work needs to be done to determine how games that effectively and playfully communicate STEM information can be constructed and deployed, there is some existing research documenting such effectiveness.

One major finding is that good games motivate players and can broaden their interests (Egenfeldt-Nielsen, 2006). Games can introduce players to the idea of environments as constructions— assemblages of parts that can be wondered at, explored, taken apart, studied, and rebuilt. Games such as *Neverwinter Nights* not only allow players to play in the world, but also provide players with the opportunity to "mod" the world. They can create their own modifications of the play environment and then publish them so that others can play their new version of the game (Kaplan-Rakowski & Loh, 2010). Play worlds can expose students to specific systems and networks of systems to help them see the way that things are connected and how their actions can affect individual parts. These concepts are fundamental to the sparking of curiosity about science, math, and engineering, which are based on our desire to understand ourselves, the world around us, and how everything works.

Minecraft, for example, is now one of the most played games in the world (22 million players) and is being used in both high school and college classrooms because the development team has specifically sought collaborations with educators to both implement the game in educational environments and study its effects (http://minecraftedu.com). *Minecraft* is a massively multiplayer online role-playing game (MMPORG) where players can construct structures out of a variety of different materials and then navigate through the worlds that they and others have built to accomplish a variety of different tasks. This game has been used successfully to further STEM education in multiple settings (Short, 2012) (see more in Case Study Two).

Another finding is that games can provide players with the opportunity to learn mathematical and scientific concepts intuitively rather than symbolically in the same way that a person can learn to play the piano without knowing how to read music (Devlin, 2013). Many schools begin teaching with the symbolic representation—numbers and graphs, for example—rather than introducing the concepts first and the symbolic representation afterward. Singapore math is taught according to the latter system (Hoven & Garelick, 2007). Games work similarly in that players can see the importance of understanding how the physical environment works to succeed in the game. In *Angry Birds*, for example, players have to intuitively figure out what kind of projectile to use and the angle and amount of force with which to launch it. These considerations involve thinking scientifically. Some educators have capitalized on this and are using the game in the classroom to teach how objects move through space and the math and science needed to calculate trajectories (Crecente, 2011).

Other findings include the proven effectiveness of using games for motivating and reinforcing the repeated practice necessary to become adept at the kinds of complex skills required in many STEM fields. Educators and developers are collaborating to build games specifically to introduce students to subjects in a way that makes repeated practice intrinsically motivating. Universities have started game development degree programs on their campuses that allow faculty to work together with students in STEM subjects to create games that reinforce specific skill sets such as mechanical engineering (Coller & Scott, 2009). Games are also increasingly being used in healthcare. *Atendiendo el Parto en Casa* (Bertozzi et al., 2013), for example, is being used to train midwives in developing countries how to deal with potentially fatal complications. Another game, *Underground*, creates an environment in which doctors, aspiring doctors and anyone who is interested can learn the motor skills required for laparoscopic surgery (Grendel Games, 2013) (see Case Study Three).

Case Study: Scenario-Based Games for Science (*Plague.Inc* and *Underground*)

Some developers have created scenario-based games for communicating science knowledge. These games immerse the player in an environment in which they must learn about a specific problem and acquire a specific skill set to survive in the game. *Plague.Inc*, for example, is a top-rated game for the Android platform. The premise of the game is that the player wants to infect all human beings and thereby eliminate humankind from the Earth. In the course of doing so, players learn a great deal about infectious diseases, how they spread, and how to infect (and also protect) populations. Through the play of the game, players also have to learn geography and demographics, how viruses mutate, and how to make a virus maximally virulent. By providing a goal that is the opposite of what might be expected—destroying fellow human beings rather than saving them—players can not only enjoy the gameplay, but also enjoy the thrill of breaking taboos, which can significantly add to a game's appeal (Bertozzi, 2008).

Other games can be more straightforward in their approach. Bertozzi's Engender Games Group lab, for example, has created a game aimed at educating midwives in developing countries (Bertozzi et al., 2013). Traditionally-trained midwives can make errors, which result in the death of the mother or the neonate during labor and delivery. In the developing world, midwives are often not literate, which further complicates training them. Using a scenario-based video game, midwives can play through the results of different actions and see how outcomes can improve using alternative methods (Cohen, Cragin, Wong, & Walker, 2012; Cragin, DeMaria, Campero, & Walker, 2007).

The Grendel team in Holland released a game, *Underground*, aimed at teaching surgeons (and prospective surgeons) how to acquire the physical coordination necessary to be skillful at laparoscopic surgery (Grendel Games, 2013). A local hospital discovered that the enormous amount of money that they had invested in a lab where physicians could practice their skills went to waste because physicians found the exercises in that lab to be extremely boring. Grendel's scenario-based game, with its compelling story and credible goals, which required players to become adept at using certain manual skills, was a much more successful method of encouraging physicians to exercise their skills in this area (GoogleTechTalks, 2012).

Assessment Considerations

There are now a plethora of games purporting to teach STEM subjects and it is very difficult to determine which ones are most effective for which contexts or learners. Given that there are not yet any professional rating or ranking systems to inform educators about which games are most effective in reaching specific teaching goals, the following questions can help an educator determine if a game is worth using for STEM learning. These questions are drawn from Norman's previously mentioned framework (1994) and from usability studies on interactive applications in general (Nielsen, 2000).

1. **Does the game have a narrow, specific, measurable outcome?** Look for games that have smaller and thus more achievable parameters for success.
2. **How long is the game?** Consider how long students will be playing the game and look for games that realistically promise what can be practiced or communicated in that amount of time.
3. **Is the interface clear and understandable for the target audience?** Many games present the player with challenges, but the user interface is not clear. When players get stuck, they may not be able to figure out how to get out of the situation. Good games include tutorials that walk players through gameplay or offer help sections.
4. **Has the game been run through cycles of usability and outcomes testing to ensure that stated goals are being met?** For example, if the game says that it is going to teach students to memorize and implement the multiplication tables, the company website should have usability and outcomes testing data to demonstrate effectiveness.
5. **Reputable third party assessment and endorsement of games can also help.** Ratings may or may not be useful. Games may be highly rated because they are fun to play; it is more difficult to find ratings assessing effectiveness.
6. **Does the game have internal means of measurement and reward that encourage players and promote continued engagement?** Players love to be given feedback. Scoreboards, badges, positive and negative sounds that respond to player behavior are all means by which games can keep players informed about how they are doing. Good educational games can integrate this assessment with the learning goals of the game. It is helpful for teachers if in-game assessments can support external assessment.
7. **Does the game provide educators with access points so that it can be integrated into existing classroom activities?** It is important to remember that games do not need to stand alone as learning tools. Teachers must integrate them into their own specific classroom environments in the same way other media are utilized. Thus, educator input into the development process is very useful. Game developers need to hear from educators about how this aspect of games can be improved.

Future Needs

Given the fact that using video games in the classroom is a relatively new phenomenon, educators currently have little guidance about how to use them effectively. Many schools now provide students with tablets (such as iPads) and encourage educators to integrate them into classroom activities. These efforts have coincided with an increased push for core competencies and outcomes assessment from the government and other agencies. It is essential that schools, educators and developers work together to find a way to develop and deploy games that foster an interest in and practice competencies in STEM subjects. Teachers cannot be expected to be able to review games and determine what will and will not work in the classroom without formal structures to assist them.

Case Study: Modding an Existing MMORPG with *Minecraft*

Rather than creating an entirely new game, educators can use existing games for educational purposes. The benefit of doing this is that the challenge of creating a compelling and fun experience has already been accomplished; now the game just needs to be implemented in a new setting. *Minecraft* is a sandbox game that provides players with a wide range of materials and tools and a great deal of freedom to do whatever they want inside the game space. The passage of time is simulated in the gamespace; day occurs and then night falls. During the day, players can accumulate materials and build things with them. At night, enemies emerge and it is important to have created structures that protect players from harm, otherwise death and destruction ensues. The game simulates the challenges living beings face in a natural environment and therefore many aspects of gameplay can be related to myriad scientific fields. To play the game, players must intuitively grapple with the principles of physics and architecture to put together structures that can protect them from enemies. They have to learn and use economic principles to acquire goods, resources, and capital so that they have the means to construct adequate protection. Many players create elaborate versions of structures that exist in the real world (e.g., the Taj Mahal) or in fictitious worlds (e.g., the Starship Enterprise). Educators are currently using this game to introduce and practice a range of engineering and science concepts (Short, 2012; West & Bleiberg, 2013), such as Bob Kahn's implementation in Brentwood Middle School (2013). There are many resources for educators at minecraftedu.com, including a wiki to help teachers and players answer questions and develop innovative ways to use the game.

Some games allow players to modify the game (known as "modding") by giving them access to the source code and encouraging them to come up with their own content. There are many games that leverage player interest to create new content in existing game worlds. Such games open their worlds to modifications by players who are able to build new sections of the game and then see what happens when players play inside of them (Soflano, 2011). *Minecraft* encourages modding and this aspect of the game has been utilized to teach and practice coding of artificial intelligence agents in game worlds (Bayliss, 2012). As both developers and educators come to recognize the potential benefits of games for education, we will see more targeted examples of gameplay that teach specific concepts.

Best Practices

Educators seeking games that will encourage, educate, and promote practice with STEM subjects should be aware of the fact that many games claiming to do so fail to meet the criteria for effective learning tools. This will change as the industry matures and educators and developers create and test new products and develop means for measuring effectiveness. At the moment, there are few directories or other tools for educators to use to find games that have proven effective. Educators should seek out games with a narrow focus with goals that appear reasonable and achievable. They should look for games that have been tested and can present evidence of outcomes assessment and usability analysis. Most importantly, games should be fun. Otherwise, they are simply interactive training environments masquerading as games. A good game motivates players to want to engage with it. STEM games should foster a sense of wonder and appreciation of the challenges involved in learning complex natural phenomena. Given the increased focus on the potential of games for educational motivation and achievement, games are attracting more funding (DeLoura & Metz, 2013) and more rigorous forms of assessment (Clark et al., 2013). This will certainly result in the development of better games and the means to integrate them into curricula.

Resources

Games

3rd World Farmer
Angry Birds
Big Seed
FoldIt
Extrasolar
EyeWire
Minecraft
Motion Math games
Newton's Playground
Plague.Inc
Rube Works: The Official Rube Goldberg Invention Game
Save the Seas
Sid's Science Fair
World of Balance (http://smurf.sfsu.edu/~debugger/wb/)
Wuzzit Trouble

Books

Baek, Y.K. (Ed.), *Gaming for Classroom-Based Learning: Digital Role Playing as a Motivator of Study.* Hershey, PA: IGI-Global.
Devlin, K. *Mathematics Education for a New Era: Video Games as a Medium for Learning*
Gee, J. *What Video Games Have to Teach Us About Learning and Literacy (Second Edition).* New York, NY: Palgrave Macmillan.

Ifenthaler, D., Eseryel, D & Ge, X. (Eds). *Assessment in Game-Based Learning: Foundations, Innovations, and Perspectives*. New York, NY: Springer
Klopfer, E. *Augmented Learning: Research and Design of Mobile Educational Games*
Squire, K. *Video Games and Learning: Teaching and Participatory Culture in the Digital Age*

Websites

MinecraftEdu: Bringing Minecraft to the Classroom (http://Minecraftedu.com)
Educade (http://Educade.org)
Common Sense Media (http://www.commonsensemedia.org (see sections for STEM games)

Consortia & Labs

STEM Education Coalition (http://www.stemedcoalition.org/)
The New Media Consortium (http://www.nmc.org/news/get-technology-outlook-stem-education-2013-2018)
VirginaTech School of Education STEM Education Collaboratory
(http://www.soe.vt.edu/STEM/collaboratory.html)
The Institute for Advanced Learning and Research STEM Internships (http://www.ialr.org/index.php/advanced-learning/k-12-programs/stem-internships)

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