Beyond Textbooks and Lectures: Digital Game-Based Learning In STEM Subjects

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"Why read about ancient Rome when I can build it?" (Moulder 2004)

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Abstract: *This paper focuses on the growing movement of digital game-based learning and the empirical evidence surrounding new research. How digital game-based learning can benefit STEM subjects (science, technology, math, and science), simulate intricate, real-world challenges and facilitate higher orders of learning is explored. Unique features of games that traditional education cannot provide as well as the barriers of implementation are discussed. The paper concludes by encouraging open source initiatives and suggesting further research in several specific areas before game-based learning is implemented on a large scale.*

The State of the Science Classroom

With so much diversity in a single nation, it comes as no surprise that we have many different learners in the same classroom. There is a diverse and complicated mix of students with different abilities, motivation, interests, and upbringing. While Johnny sits in the back of science class feeling lost and confused, Jill is feeling bored and belittled by the lack of challenges. Johnny may learn best with a hands-on experiment while Jill does not find the tradition lecture stimulating. One brave teacher not only has 23 other Jills and Johnnys, but also must finish the day's curriculum in 50 minutes and hope the students absorb enough to pass the required state and national tests so she can keep her job. While standardized testing is currently the most efficient and easy method of evaluating student knowledge, it has also trapped learners into a system of isolated facts and events. It cannot accurately measure a student's creativity, collaboration, interpersonal communication, innovative thinking, or system thinking (Rothman 2011). In the wake of standardized testing, school philosophy has become 'basic skills for all.' Rather than adapting the curriculum to the learner, we are forcing learners to adapt to the curriculum.

Another problem in the equation is rapidly evolving technology. Today's students, also referred to as "digital natives," have grown up with powerful computers and advanced smartphones (Thai et al. 2009). Digital natives absorb multiple sources of information, quickly and simultaneously. Technology not only assists them in everyday life, but has become part of the way they express and define their lives. In 2007, Pew Research Center found that "of the 93 percent of 12 to 17 year olds who now use the Internet, *nearly two-thirds* use it not just to access information but also to create it and share it—uploading their own digital creations, writing blogs, or maintaining personal Web pages" (Jerald 2009). YouTube stars, bloggers, digital artists, machinima creators, fan fiction writers, and online community members have made media novelties and a name for themselves on the Internet.[1] As a result, a divide is growing between the digital world and the classroom. The current school system is not set up to foster the creativity that is being produced in the virtual world. School systems resist and push away this creativity by banning phones, social networking sites and games for reasonable safety and liability concerns. However, to stay connected and understand digital natives, schools need to adapt to the world the students are living in.

How do games fit into all of this? Reminiscing about the times of Pac-Man and Pong, one might realize how quickly game technology is evolving. While the early games of the 8-bit era were simplistic in design, games today are full immersive virtual environments with realistic graphics, engaging character dialogue, and dynamic storylines the player can control. The world students are living in at school is very different from the ones at home. Yet "the promise of games is that we can harness the spirit of play to build new cognitive structures and ideas of substance" (Klopfer et al. 2009).

This paper explores digital game-based learning as a way to bring higher learning objectives into junior high and high school classrooms while also bridging the digital gap. The first section will discuss the crucial new 21st century skills needed for global competition and

[1] **Machinima** is the creation of animated movies using a real time, 3D virtual environments. "Machinimists" often use video games to make these animations, which they share on YouTube, game forums, and other online communities. **Fan fiction** includes stories or poems written about existing media, including games, books, movies, or television shows. Popular fan fiction writers often have large fan bases and extremely engaging, erudite stories on sites like www.fanfiction.net. Machinima and fan fiction make up what is often called "fan labor."

why current teaching methods and tools need to evolve. The second section will discuss several leaders in digital game-based learning and the current use of games as a vehicle for learning. The third section will explore what games can offer traditional education, which has a heavy emphasis on the passive consumption of knowledge in lecture format. The fourth section will explore why games are impressive mediums for facilitating higher learning objects in STEM subjects. The fifth section will explore some of the ways games can be implemented into education, as well as the barriers. The sixth section offers policy suggestions, particularly in the field of research.

STEM Education in the United States

Benjamin Bloom, who proposed the well-known Bloom's Taxonomy of learning objectives in the late 1950s, would probably agree that classrooms are stuck in the "knowledge" stage of simple memorization and defining. Other more advanced objectives, such as analyzing, evaluating and synthesizing, are often ignored for lack of time and relevance to the standardized test. For example, students may know all the phases of mitosis, but the significance or importance of such a process is largely unmentioned. However, these higher order skills are crucial for the 21st century's information-based economy. As a modern movement, many researchers have created several different taxonomies of what should be included (Partnership for 21st Century Skills 2009, Jerald 2009, Voogt and Roblin 2012). However, communication, collaboration, innovation, system thinking, technology literacy, and global system awareness are skills that are most commonly noted. Students need to be able to "work with incomplete information, adapt to changing conditions, manage complexity, and fluidly create and share knowledge" (Rosebaum et al. 2007). These skills are not mutually exclusive from Bloom's Taxonomy, which states that higher order skills include analyzing (compare, categorize and examine), synthesizing (design, hypothesize and invent) and evaluating (critique, assess, and appraise) (Clark 1999).

Despite efforts to push advanced learning, the American school curriculum remains in the 19th century as the United States' global position in STEM declines. While there was a two-point gain in National Assessment of Educational Progress (NAEP) scores from 2009 to 2011 for 8th graders in science, 65% of those students are performing under or only at basic standards while a mere 2% meet advanced standards (Nation's Report Card 2011). This is also reflected in the Program for International Student Assessment (PISA) scores as the United States scored lower than the Organization for Economic Cooperation and Development (OECD) average in both math and just barely average in science (Fleischman et al. 2009). In fact, America's 2009 mathematics score was not measurably different from the score in 2003. On the science literacy scale, in which levels 4, 5, and 6 represent higher order skills, only 29% of American students performed at levels 4 and above, meaning the majority of students display very basic science literacy (Fleischman et al. 2009).

Science, technology, engineering, and math are vital to the American economy. The Department of Commerce found that "technological innovation has been responsible for as much as 75 percent of the growth in the American economy since World War II," and "the societal return on investment from publicly funded research and development are estimated to range from 20 percent to 67 percent" (Atkinson and Mayo 2010). STEM innovation also leads to job growth, competitive advantages, and higher standards of living. While the United States' test scores have stayed stagnant, the STEM labor market has not. Technology's rapid growth has steadily increased the demand for engineers and innovators. As America fails to produce enough domestic STEM talent, firms are forced to look overseas for foreign workers and, by 2002, 20%

of STEM occupations were filled with foreign-born workers (Atkinson and Mayo 2010). However, "we may not be able to rely on high-skill foreign STEM talent too much longer, as other sending nations, like China and India, successfully grow their own tech economies and universities" (Atkinson and Mayo 2010). Therefore, improving STEM education has become a national movement. Many have realized that the United States cannot improve unless the methods and tools of learning are upgraded. National movements, such as *Educate to Innovate*, focus not only on improving the United States position in STEM but also on new methods to help students think critically in these fields. One such progressive method includes game-based learning, which is gradually being considered as a valuable vehicle for learning.

Games as a Vehicle for Learning

Before making an argument for digital game-based learning, it is imperative to define a digital game. In this paper, a digital game is any game on a console, handheld device, smartphone, or computer, including browser games. It includes different genres and types, including simulation, augmented reality, and alternate reality games.[2] James Paul Gee, the Mary Lou Fulton Presidential Professor of Literacy Studies at Arizona State University, describes a game as two pieces: the actual game but also "the whole social system of interactions the players engage in inside (for multiplayer games) and around the game (sometimes called the meta-game)" (Gee 2011). Gee says this meta-game may be where actual learning occurs as players share strategies; ask and answer questions; build "mods" (modifications for the game's design or

[2] **Simulations** and games can often blur in definition; games tend to have a set of rules and a clear objective, whereas simulations "are generally defined as representing one symbol system through another" (Squire and Patterson 2010). For example, a pilot trainee might use a simulation to experience flying a helicopter, while a player in SimCopter will also fly a helicopter but will rescue or transport people to accrue money or points. **Augmented reality** (AR) is a "simulation that combines real surroundings with virtual simulated information to convey authenticity in large scale scientific investigations" (Klopfer 2005). An **alternate reality game** (ARG) is defined as a "game you play in real life and not in a virtual environment by using real life as a platform and transmedia to deliver the story" (McGonigal 2011). For example, Chore Wars turns household work into a quest where players earn virtual gold for completing different "missions" like cleaning the bathroom or taking out the trash.

graphics); research game algorithms; and create communities. This will be discussed in more detail in the next section.

Games often have a negative stigma attached to them and are classified as a violent and mindless activity. Parents may see them as a waste of time, and teachers might see them as competitors for students' time; however, gameplay statistics are actually quite surprising. Many assume the typical gamer is a young teenage male furiously mashing buttons during a *Mortal Kombat* match. In fact, 47% of game players are female and the typical game player is 30 years old (ESA 2012). Researchers have found no evidence that frequent gameplay leads to social isolation, and "60 percent of frequent gamers play with friends" while "33 percent play with siblings and 25 percent play with spouses or parents" (Salen 2008). Motion-based games with multi-player emphasis, like *Zumba Fitness* and *Just Dance 3,* were two of the top 12 video games for 2011 (ESA 2012). Games can also be rich with learning and social activity. Top selling games like *Mario Party*, *Brain Age* and *Wii Sports* on the Nintendo's Wii emphasize social play. *Sid Meier's Civilization*[3] is strategic and packed with history, challenging players to take on the role of Gandhi of India or Catherine of Russia and build their civilization. *Civilization* players must expand cities, manage trade relations, address food shortages, advance technology, and find resources to make sure their civilization survives the test of time. *The Sims* allows players to experience the constraints of a family budget and the difficulties of balancing a job, social life, and hobbies. *Roller Coaster Tycoon*, a construction and management game, challenges players to design roller coasters under the constraints of physics.

Using games to educate and train is not a new concept. Games have been used in everything from military and employee training to customer engagement (Hays 2005, Fowler

[3] Many games in this paper are explained in greater detail in Appendix A, particularly those that are ideal for education.

1994). So it is a bit counterintuitive that games are considered effective in teaching strategy to firefighters or simulating surgery for physicians, but they are not used in the classroom where they could have the greatest impact.

Educational games became popular in the 80s with the growing number of personal computers and the approval of parents. As competition grew, "big box stores required publishers to offer products at lower prices, and for lower profit margins" while publishers simultaneously had to distinguish their products by "licensing characters with built-in market appeal (Rug Rats, Sponge Bob, etc.) that would stand out on the shelf" (Klopfer et al. 2009). Meanwhile, the surge in technology led to high-quality entertainment games that made low-budget educational games pale in comparison, and it was not long before the educational game industry collapsed. This memory of failure continues to linger, and "few companies are willing to make the investments needed to develop such games since there is yet no demonstrated market" (Federation of American Scientists 2006). However, games are now being revisited as educational tools by several leading organizations, such as MIT's Education Arcade and Games-to-Teach project, Woodrow Wilson Foundations' Serious Games Initiative, University of Wisconsin's Games Learning Society, the Federation of American Scientists, the Bill and Melinda Gates Foundation, and the U.S. Department of Education.

Games offer a wide variety of benefits, depending on the game. The most obvious is the increased motivation to learn or pay attention. Specifically, games can become a facilitator for self-directed study and research; when students enjoys a specific area in a game, they become more inclined to search it online, read a book about it, or watch a documentary. Kurt Squire, who is a research manager at MIT's Games-to-Teach Project, implemented *Civilization III* in classrooms and found many students were doing research at home about their particular civilization's strengths and weaknesses (Squire 2011). Games can also accommodate a variety of auditory, tactile or visual learning styles since games immerse students in sound, touch, and sight. However, games offer much more than engagement and fun. The next section will address the unique features of games and why games "represent a technology that illuminates how the human mind works" (Gee 2008).

What Can Games Offer Traditional Education?

In order to make a compelling argument for game-based learning, students must learn something from games that traditional education cannot provide. James Paul Gee and many other researchers argue that games follow several learning principles that make them better instruments for learning than the traditional classroom structure (Gee 2008). First, good learning allows a student to be a producer rather than a passive consumer of his own learning. In a typical classroom, a teacher lectures while students passively listen and take notes without context or application. However, games are interactive; that is, "when the player does something, the game does something back that encourages the player to act again" (Gee 2008). Their actions shape the game world around them, causing the player to reflect on their decisions and form hypotheses. Clark (2009) explains that traditional education treats students as passive recipients while games allow them to be active members in their own education which allows for more self-directed, creative, and engaging learning.

Games also feature inquiry-based learning. They rarely coddle players during the learning curve; instead, games hold players to high expectations, and players must ask questions and engage in experimentation (Gee 2008). For example, the commercial physics-based puzzle game *World of Goo* does not give any information at the beginning of gameplay. Therefore, "the only way the player can figure out the goal of the level is by engaging in exploratory behaviors, observations, reflections, and continuous hypothesis making and testing" (Shute and Kim *in press*).

Games also allow players to customize their difficulty levels or styles of play. Students in the traditional classroom may feel material is too hard or too easy, and they cannot try on different learning styles or use another problem solving method without the risk of failing or receiving a bad grade (Squire 2011, McGonigal 2011). Games make it less risky and pleasantly frustrating to fail. Players know the game is possible to beat with enough practice, and "good games adjust challenges and give feedback in such a way that different players feel the game is challenging but doable and that their effort is paying off" (Gee 2008). Many games also allow players to win or play in multiple ways, allowing players to take on challenges with methods that suit their strengths or try a new problem-solving approach.[4]

Traditional classrooms tend to focus heavily on facts, definitions and isolated events, leaving little time to create relationships between ideas or to reflect on how events affect a global society. Yet, learning is enriched when students can see how their strategies and ideas fit into a bigger, interconnected system. As a player learns the game world, he or she can see how elements are interconnected and affect the world. This leads to another learning principle: "humans are poor at using verbal information when given lots of it out of context and before they can see how it applies in actual situations" (Gee 2008). Games, however, act as learning scaffolds, delivering information to the player just in time when they need to use it. Game designers are constantly considering what players need to know for their next challenge; this helps break up content so that facts are learned as a side effect from simply participating in these challenges. For example, in the popular game *SimCity*, players come into the game knowing little

[4] In the game *Civilization*, there are several ways to win. The player can win the space race (technology), take over all the other civilizations (military), fill out five "culture trees" to develop the Utopia project (culture) or win the most votes in the United Nations (diplomacy). Therefore, there are both diplomatic and militaristic approaches.

about city planning. The game does not give the player a lecture or a textbook (although they may have a reference guide), but encourages experimentation with commercial and residential zoning and taxation while providing guidance and information whenever the player needs it. Players automatically learn the urban management vocabulary and economics embedded in the game's design through this experimentation.

As players explore their game world, they also create memorable, rich experiences which can be used to retrieve and reflect upon knowledge. They are basically learning by doing, and this is also known as *situated learning* where "people learn through active experiences and critical interpretation of their experiences via personal reflection and interpersonal discussion" (Shute and Kim *in press*). Traditional classroom lectures rarely create these meaningful experiences without interactive or hands-on activities. Games use "stories, characters, and other environmental elements that produce a unique experience allowing them [players] to later recall addressed subject matter" (Clark 2009). In Virginia Tech's *CandyFactory* game, students have a chance to partition fractions virtually in order to serve customers their desired candy bar size. Dr. Evans, the principle researcher for *CandyFactory,* explains that students are not only able to visualize and manipulate fractions but also to understand the concept of fractions as a measurement. Rather than drilling skills that students already know, *CandyFactory* teaches the concept of partitioning and then challenges students to apply those skills and learn by doing (Evans).

For those that fear 3D virtual environments are too detached from reality, augmented reality (AR) handheld games are also becoming a popular option for game-based learning. AR games work by integrating virtual data and a storyline into real world settings. That is, players will play in a real world location, such as a lake or school, but come across virtual characters and use virtual tools that are displayed on the handheld device. Therefore, "novel opportunities exist for learners to interact with the physical environment, literally reading the landscape as they conduct environmental investigations or historical studies" (Klopfer et al. 2005). Proponents claim that handheld AR games "provide less simulated sensory input, but remain closer to the actual world and can take advantage of its affordances for authenticity" (Rosenbaum 2007). Handheld games also tend to feature heavy face-to-face collaboration between students, who are often placed in groups. MIT's Education Arcade specifically created several AR handheld games, such as *Mad City Mystery* and *Environmental Detectives*, to determine the magnitude of this communication. When assigning students to groups or to professions (medical doctor, environmental scientist, and government agent), students eagerly worked together using each profession's unique skill to locate a toxin leak (Klopfer et al. 2005).[5]

As mentioned before, the meta-game may be where the learning actually occurs, whether it is through a forum, fan-site, discussion board, or a physical gaming community. Many players compare strategies, ask for help, give advice, share modifications (mods) they have made for a game, or even produce videos or artwork based on the game. Game developers often provide smart tools for players to develop mods to either improve or tweak the game design and graphics. Kurt Squire explains that these mods represent "design literacy," a term coined by the New London Group as an important 21st century skill. During design literacy, a player decides "what message he wants to convey through the mod and how to work within the modding tool's constraints, and then reflects back on how it will be received by the players" (Squire 2011). While the game might teach the player certain skills or information, the meta-game is where the student can perform in-depth thinking and engage in collaboration.

[5] For example, while doctors could give physical exam and had sole access to patient records, only the environmental scientist could take air and water samples.

Games in STEM Subjects

STEM education is very limited when it is not experienced. Reading about the greenhouse effect or static equilibrium can only explain so much until one understands how those concepts operate and fit into the surrounding world. Many classroom laboratory experiments tend to be rigid, predetermined recipes with, ironically, very little actual experimenting. Games encourage students to make their own experiments and hypotheses without a strict or set direction, which make them perfect for STEM subjects. Games give life to definitions and abstract concepts by letting the player experience them. For example, "the inverse square law of gravity is no longer something understood solely through an equation; students can gain virtual experience walking on worlds with smaller mass than the Earth, or plan manned space flights that require understanding the changing effects of gravitational forces in different parts of the solar system" (Shaffer et al. 2004).

While puzzle games can develop logic skills and computer games can improve spatial orientation, it's really the mechanics of a game that facilitate STEM learning. STEM concepts are notorious for quickly and heavily building on each other. Falling behind can be a huge disadvantage for the next lesson; e.g. if addition is not learned, learning multiplication will be very difficult. Students in a traditional classroom may not know if they understood a concept correctly until they fail or pass an assignment, which may affect how they feel about a subject. However, games provide instantaneous feedback. When decisions are made in a game, the game will either reward players for their efforts or they will not advance levels. Until a player understands a specific concept, like static equilibrium in *World of Goo*, he or she will have to keep adjusting a strategy according to the game's feedback until the concept is understood and mastered.

Due to classroom time constraints, teachers must move quickly through lessons and rarely have the time to take a subject in depth which can mystify the subject for the student (Atkinson 2012, Honey and Hilton 2010). Each student moves at a different pace, and if a student falls behind he or she will often pick up a shortcut to the answer without bothering with the conceptual understanding. Games, however, often have an adaptable learning rate that is set by the user, and games can be used inside or outside the classroom. Students that have trouble grasping a difficult and complex STEM concept can spend more time exploring it, while those that are ready to proceed can continue to be challenged. Websites like Khan Academy provide hundreds of video lessons on everything from why dividing by zero is undefined to the potential energy stored in a spring. This allows slower-paced students to re-watch older lessons while giving more advanced students the opportunity to expand their knowledge base. Khan Academy's practice section employs a game-based design, allowing students to earn achievements, titles, and badges while working through problems. More advanced students can continue to challenge themselves as they work their way up the "knowledge map" to titles like "Master of Trigonometry" and "Copernicus." Slower-paced students can practice their weak areas until they are ready to proceed.

Games are able to make learning socially relevant. As concepts become more difficult in school, "students no longer see science as connected to the real world and lose interest in the subject" (Honey and Hilton 2010). By participating in an immersive environment or storyline and taking on the role of a scientist or mathematician, players can watch how their knowledge applies in these realistic simulations. This is especially important for mathematics where students see little value to the algebra or calculus they are learning. In *Quest Atlantis*, a student "takes on the role of statistician, and in-game characters ask the student player to analyze data to determine whether surveillance cameras or an increased police presence will make the virtual town safer. The next time the student returns to this virtual town, he or she may encounter cameras on every building or a police officer on every corner" (Barab 2009). Students can see how their skills and knowledge application can make change and have dynamic consequences, which encourages system-thinking. If these experiences are emotionally stimulating, it also makes knowledge easier to recall. In fact, when the *Quest Atlantis* experimental groups were tested two months later, "the students who learned through the virtual game remembered more science content than the traditionally taught students" (Barab 2009).

Modern technology has made it possible for players to experience the impossible through games. Whether they are watching their creations evolve in *Spore* or investigating a boneyard on a foreign planet in *Martian Boneyards*, games "enable learners to see and interact with representations of natural phenomena that would otherwise be impossible to observe" (Honey and Hilton 2010). Through games, teachers can take their class to the moon or collaborate on what is causing an epidemic in fictional *River City*. In *River City*, students work together to "conduct their scientific investigations in a virtual historical town—populated by themselves, digitized historical artifacts, and computer agents—in order to detect and decipher a pattern of illness that is sweeping through the virtual community" (Ketelhut 2007). While the class could simply read about how an epidemic spreads in a textbook or see a few diagrams, games let students experience it and actively seek out the information themselves, encouraging students to use problem-solving and scientific inquiry skills. Games allow students to immerse themselves in a concept without a linear, constricted approach.

Games often challenge players to take on the roles of professionals, allowing players to problem solve with a new frame of reference. These games, often referred to as "epistemic games", allow students "to learn through participation in authentic recreations of valued work in the world, and thus give educators an opportunity to move beyond disciplines derived from medieval scholarship constituted within schools developed in the industrial revolution" (Shaffer 2006). *The Pandora Project* challenged students to weigh the benefits and scientific progress against the limitations and ethics of xenotransplantation using their stakeholder's perspective, which included the federal government, the Animal Rights Coalition, and a biotechnology company (Shaffer 2006). When Shaffer conducted a study around *The Pandora Project*, he found that "students gave much more extensive answers in the post-test, bringing up the interests of all stakeholders instead of just their opinions or concerns" (Shaffer 2006). Students also created more in-depth concept maps than in the pre-test analysis and used the professional lingo of their stakeholders that was developed as a side-effect. Through the game, students not only learned about xenotransplantation and how it works, but they evaluated the ethics, implications, and consequences of implementing it.

Games can also prepare students for the technology they will be using in future STEM careers. Many games indirectly assist in computer or mobile technology literacy. For example, "the MIT TEP [Teacher Education Program] has been building simulations on handheld computers that involve K-12 students in authentic activities such as large scale environmental engineering investigations, genetic data collection and analysis and epidemiological studies that track the progression of disease through population" (Klopfer 2005). Feeling comfortable with technology is crucial for students in the 21st century and essential for technology-heavy fields like computer science, engineering, and science. Augmented reality games that use handheld devices allow students to experiment with technology while being immersed in a subject. Students can learn how to research and compile data while establishing a comfort, respect, and understanding for technology. MIT's *Environmental Detectives* had "students role-play environmental scientists, investigating a rash of health concerns on campus linked to the release of toxins in the water supply" and were given handheld devices, which teams then used to "compile their data using peer-to-peer communication and synthesize their findings" (Klopfer 2005). Building games can also improve technology literacy. Under the Educate to Innovate movement, the National STEM Video Game Challenge[6] encourages students to create games of their own based around STEM concepts. In the 2011 competition, students used basic programming tools like *Scratch*, *Gamemaker*, and *Kodu* to create games that challenge other students to navigate a maze using multiplication, learn about recycling, or understand Darwin's finches. Creating games allow students to actively participate in their learning and become producers of knowledge. Students can express their creativity while teaching concepts which facilitates their own reflection and deeper understanding of a subject. Creating games also prepares students who may pursue computer science, information technology or another career in technology (Klopfer et al. 2005).

How to Use Games in STEM Education

There are multiple ways to implement game-based learning, and not all of them have to be utilized during class time. However, games are great supplements for a lesson plan as they can either reinforce material or set up a teaching environment. Squire notes that "games excel at creating teachable moments for teachers to explain investigative and model-building skills" (Squire 2011). Games can place students in situations they are unable to experience in a school or even in real life. Games like *Supercharged!* allow concepts like electrostatics to come to life. In *Supercharged!* students control a spaceship that places charged particles which allows them to

[6] www.stemchallenge.org

see how the laws of physics work and test them rather than just reading about them in a textbook (Squire 2011).[7] Games also create teaching opportunities for the students. Pairing students to one computer encourages students to help each other and collaborate during gameplay which may produce new perspectives and strategies. Some students may be more advanced than others, allowing those students to teach and thus reinforce the material they already to know to the less advanced student. Teachers can use games like *Supercharged!* to enrich a lesson plan with material that can be explored and analyzed instead of passively consumed. Games can also be used to combine multiple disciplines. Mr. Plank, the Associate Vice President for Research at the University of Virginia, collaborate with professors from many fields, including architecture, business, and resource management, to create the *UVa Bay Game*. This game allowed students to work from multiple perspectives, like farmers, policy-makers, and businessmen, to see how their actions as independent agents impacted a global system. Instead of limiting subjects to their respective fields, students had a chance to see how one field was interconnected with another one, encouraging system thinking (Plank).

Squire and Patterson studied how science games could be used in informal settings, such as after-school programs and summer camps. They note that "informal science education is unique in that it is free to operate in widely diverse contexts. Whereas schools must respond to a variety of local and national political needs, pressures, and concerns, informal science educators have significant freedom in pursuing goals germane to institutional interests" (Squire and Patterson 2010). Informal settings tend to be more flexible with time and less burdened by testing. Eric Klopfer, who has implemented augmented reality games about virology and epidemiology in informal school settings, "has shown conceptual changes in how participants think about

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[7] *Supercharged!* was implemented in both a 9th grade and college level MIT course. Students in the college course showed higher learning gains than their control group counterpart. Both experimental groups also showed a deeper understanding of electrostatics in an oral examination than the control group (Squire 2011).

diseases and how they prioritize steps in conducting investigations" (Squire and Patterson 2010). Squire, who started a summer program based around *Civilization*, found that students were taking the game home to create modifications or performing research on their civilization in self-directed study (Squire and Patterson 2010).

Games are also being considered as prototypes for the next generation of tests (Gee and Shaffer 2010). Games are not only able to test skills like problem-solving and scientific inquiry that standardized tests cannot capture, but are argued to be less expensive and more practical than performance assessments (Rothman 2011). Rather than testing what students already know, Rothman explains, game-based tests can show what the student can *do* with that knowledge. They "make it possible to measure complex abilities because they allow assessors to observe students' activities in ways not possible with even the most sophisticated paper-and-pencil tests" (Rothman 2011).

Barriers to Implementation

As with any change in education, there are multiple barriers to implementation. Schools are wary of purchasing material that is not relevant to standardized tests and not in line with curriculum requirements. Games can also be expensive to maintain or purchase. However, many have found a way to get around this cost, such as pairing students to one computer (Squire 2011), using free browser games (Mitgutsch and Alvarado 2012), or creating applications for the smartphones that many students already own (Klopfer and Yoon 2005, Squire 2011).

Within the school, teachers are wary about mandated change and technology. Not only do they have a requirement to help students pass the state test, but they must cover all the curriculum content on time. Teachers may not have the professional development needed to incorporate games into their lesson plans, and they might find it difficult to implement a game in a 50 minute period. Students also come with different games and technology proficiency. While some may play games consistently, some may feel uncomfortable with the technology. A discomfort with technology may disrupt any potential learning (Sandford et al. 2006). At the industry level, many gaming companies do not see value or profit in educational games, meaning the development is left largely to independent designers and research organizations. Compounding the problem, it is very difficult for these organizations to test their products as there are many barriers to conducting a pilot study in a school (Squire 2011). Even when granted access, researchers may be confronted with strict acceptable-use policies that prevent them from accessing the Internet (Evans 2012).

At the cultural level, many parents, teachers, and administrators may view games as a waste of time, violent or addicting. However, when this perception is overturned, parents and teachers can become invaluable facilitators. MIT, for example, implemented a handheld scientific investigative game called *Mad City Mystery*, in which both teachers and parents participated with students. The success for this game largely revolved around the facilitation these adults provided (Squire 2011). However, even if parents see the potential of game-based learning, they may not see the classroom as an ideal location for gameplay. They fear the constant growth of entertainment and believe it could be detrimental to a student's self-motivation and work ethic, claiming that school should not be in charge of entertaining children. However, it is exactly this label of "entertainment" that serious games[8] are trying to repudiate. Games for the classroom are not provided as a source of entertainment, though they may be engaging and compelling, but as learning tools that improve traditional education and produce

[8] Serious games are games that have a purpose other than entertainment, such as education or training. That is, "serious games intend to fulfill a purpose beyond the self-contained aim of the game itself." (Mitgutsch and Alvarado 2012).

21st century skills. Bringing games to the classroom also brings the possibility of teaching children to respect digital media, practice internet safety and establish gameplay boundaries.

Others may argue that the virtual world is just that—virtual. They are concerned that the skills and concepts learned do not apply to the real world. Indeed, "if a learner never realizes how this virtual experience relates to real-life experiences, then the game playing will have been engaging but not productive" (Barab 2009). This is a healthy skepticism, and it must be firmly stated that game-based learning rarely occurs without an engaged teacher that can encourage discussion. Students need to reflect on what they have learned and discuss it to facilitate collaboration and communication skills. In that regard, games are meant to fit into the teacher's lesson plan and not the other way around.

Recommendations and Policy Proposals

Many of the proponents of game-based learning urge school officials and teaching communities to adapt games to their lesson plans. While there is research supporting this opinion, there are many problems with the current research. First of all, there is a lack of cohesion in game-based learning research. While some central figures like James Paul Gee, Eric Klopfer, David Shaffer, and Kurt Squire work closely together in different university programs, the majority of the movement is focused on individual research projects with little open source. Numerous terms with similar meanings make research confusing, and the vast genres and uses of games have led to fragmented research that does not build on itself (de Freitas 2006). The games that are created for research are also rarely distributed or made public. Second of all, a large portion of the available empirical evidence is poorly designed. Many of the studies use very small sample sizes and do not use accurate control groups (Young et al. 2012). For example, how does a game compare to the lecture of a very engaging teacher? Few studies control for a student's background in technology, which might affect his or her outcome. Since it is difficult to perform research in schools, many of the research studies have strong selection bias as students must volunteer to participate and selection of schools is limited (Squire 2011). One literature review found that only 39 articles met their criteria for credibility out of 363 articles (Young et al. 2012). Lastly, there are no best practices for implementing game-based learning. While there have been many instances of games facilitating higher orders of learning, best practices for replicating that success are not established.

Continuing grants from the National Science Foundation, which has been a fundamental patron for game-based learning, and encouraging bipartisan nonprofit initiatives, like Digital Promise, will help facilitate research and a national movement. While some may look to the large gaming companies for participation, it is important to remember that "the high cost of game development and uncertain markets for educational innovations make investments too risky for both the video game and educational materials industries" (Federation of American Scientists 2005). However, game companies can contribute by providing modification tools in their games that allow educators to shape games to fit their lesson plans. For example, *Minecraft* developers partnered with a team of educators to create *MinecraftEdu*, a *Minecraft* modification that gives teachers more features and tools to use the game in the classroom at a discounted price.[9] Valve, the developers of the popular commercial puzzle game *Portal*, has also teamed up with educators. Not only are teachers and game developers working together to create lesson plans for *Portal*, but Valve also provides *Portal 2* and the puzzle maker to educators for free.[10]

For those interested in implementing pilot programs, professional development for teachers is imperative. Research has repeatedly shown that game-based learning works best with

[9] www.minecraftedu.com
[10] www.teachwithportals.com

a teacher acting as a facilitator for reflection, discussion, and critical thinking (Klopfer and Yoon 2005, Sandford et al. 2006, Squire 2011, Steinkuehler et al. 2012). However, teachers need to be shown how the game can work for them, rather than forcing them to work with the game. Squire's team quickly realized a rigid game-based lesson plan did not work; teachers use games in different ways to suit their teaching styles and the needs of their students (Squire 2011). Many teachers have perfected their craft with decades of experience, and "attacking educators' current practices combined with the lack of acknowledgment of current best practices only hinders the growth of the education sector" (Klopfer and Yoon 2005). Offering professional development ensures that the teachers are comfortable with the technology and can use it in the most effective manner. As Squire clearly puts it, "We may not know how any one teacher should do his or her job, but we can provide that teacher with the resources to transform individual teaching practices as he or she sees fit" (Squire 2011). ARIS[11], an open source platform for developing mobile learning games, takes this to heart in their development. ARIS allows educators to build their own mobile games and tailor them to their curriculum requirements and class structure.

Conclusion

Great educational games are available to students and can facilitate higher orders of learning in STEM education. A good game can facilitate good learning due to its immediate feedback, adjustable difficulty and gameplay style, and situated learning mechanics. Digital game-based learning has already shown great potential for enriching the education of digital natives. To secure America's position in the global economy, students must be challenged and taught critical 21st century skills, including system thinking, information synthesizing,

[11] www.arisgames.org

technology literacy, and ingenuity. Games are promising vehicles for learning these skills, if educators be taught how to implement them effectively.

While many researchers have tackled the concept of game-based learning, the research is still very fragmented. There is little cohesion, resulting in dozens of similar terms and poorly designed studies. While organizations like the MIT Education Arcade and the University of Wisconsin-Madison's Games Learning Society collaborate together and produce excellent research, there are still many unanswered questions. How do we assess whether a game is effective or ineffective? What are the best practices for implementing games in education? How will we overcome the multiple barriers in a system that is resistant and slow to change? Many have already proven that games have a lot to offer education as far as problem-solving, system-thinking, creativity, and real-world application. Now, however, is the time to focus on finding best practices for design and implementation and presenting empirical evidence to support them. Before digital game-based learning can truly be productive in an educational setting, pilot programs and well-designed empirical research studies are needed. Supporting strong patrons, like the National Science Foundation, and encouraging open source between universities will help facilitate these needs and ensure progress towards educational tools that will prepare students for the 21st century.

Works Cited

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Appendix A – Referenced Games

<u>CandyFactory</u> (Virginia Tech)
http://ltrg.centers.vt.edu/candyFactoryR1.htm
http://itunes.apple.com/us/app/candyfactory-educational-game/id533213891?mt=8

CandyFactory is a game developed by Virginia Tech that teaches the concept of fractions to middle school students based on splitting operations with partitioning and iterating. The game is unique in that it teaches concepts rather than just reinforcing material that students already know. I had the pleasure of speaking with Dr. Evans, who is the principle research investigator, about the game. *CandyFactory* is fairly new as it was developed in 2011 and is still being implemented and researched. The second version of the application featured game mechanics to increase student engagement. *CandyFactory* is available for free in the Apple store for the iPad (see second link) and is funded by a grant from the National Science Foundation.

<u>Civilization</u> (Firaxis Games)
http://www.civilization5.com/

Civilization is a turn-based strategy game (that is, it is not in real time) where players play as one of the famous civilizations, such as Alexander of Greece, Napoleon of France, Catherine of Russia, and Gandhi of India. The latest version is five, released in 2010, although many players still play previous versions. Every player (this can be played solo or online with friends) begins with a single settler and raises their small, humble city to a complex, large civilization using technology, culture, economics, and military units. The player must balance all four to have a competitive, stable, and protected civilization, but they may choose to focus on one. There are several ways to win the game, whether by winning the space race (technology), taking over all the other civilizations (military), filling out five "culture trees" to develop the Utopia project (culture) or winning the most votes in the United Nations (diplomacy).

While the game in itself is a masterpiece requiring careful strategy, the most impressive part is actually the meta-game (the community around the game). There are numerous forums dedicated to sharing solutions, offering advice, reenacting historical events, and creating mods (modifications to the game design). However, the most popular one is Apolyton. In Apolyton University, there are courses, boot camp for newcomers, and even simulations and mods about how WWIII would occur and be carried out. The purpose is not to win the game in Apolyton University, but to share information as to whether their strategy was a success or failure (Squire 2011).

<u>Environmental Detectives</u> (MIT Education Arcade)
http://education.mit.edu/ar/ed.html

Environmental Detectives is an augmented reality game that uses handheld devices with a GPS to teach students how a toxin moves. As expressed on the website, "Students watch a 60 second digital video-briefing from the University president where they are enlisted to investigate the spill of the toxin, a carcinogenic degreasing agent which is commonly found in machine shops, cafeterias, and hospitals. The goal of the game is to locate the source of the spill, identify the responsible party, design a remediation plan, and brief the president of the University on any health and legal risks so that he will be prepared for a meeting with the EPA – all within two hours. At the end of the game, students make a five minute presentation to their peers outlining their theory behind the spill."

Mad City Mystery (MIT Education Arcade)

"*Mad City Mystery* was designed to help students think like scientists, specifically to see interactions in their environment as interconnecting geochemical processes and to use scientific understand and scientific argumentation to understand key contemporary issues facing their local environment. It is a GPS handheld game meaning students could travel around with a palm pilot device to interview virtual characters and find the source of the toxin. It took place on the University of Wisconsin-Madison campus near Lake Mendota and students usually spent about 90 to 120 minutes playing." (Squire 2007)

Students were instructed to form hypotheses about the death of the virtual friend, Larry, who suddenly drowned while fishing. They then had to find evidence that supported those hypotheses (whether it is a toxin in the water/air, mercury from the fish, suicide, etc). Virtual characters (doctors, Larry's friends and family, life insurance companies claiming fraud) would provide counter-hypotheses and evidence, and students could use virtual tools (water testing kits, research documents, patient records) that were on the handheld device.

Minecraft (Mojang)
www.minecraft.net

Minecraft is described as a sandbox-building game, meaning that players design and build their gameworlds. Players use cubes of stone, wool, wood, glass, and other materials to create anything they can imagine. The game also features "redstone" which can be used to create electronic circuits that can open doors, create traps, or push a cart down a rail. *Minecraft* teachers have become incredibly creative with this game. Not only did they form MinecraftEdu with the developers, but they have created lesson plans on everything from animal cells to contour maps to geographic features. They have used it to recreate the Taj Mahal and build a digestive system that students can explore.

Portal (Valve)
www.thinkwithportals.com

Portal and *Portal 2* are challenging commercial puzzle-games created by Valve. These games are unique because they also have a rich story line and meaningful narrative, which can be rare for puzzle games. In *Portal*, the player navigates Chell, the protagonist, through the fictional Aperture Science Laboratory. Each room features a different puzzle where players must use the laws of physics, logic skills, and scientific inquiry to progress. Chell is equipped with a portal gun, which can create two portal ends that she and other objects can travel through in 3D.

Valve has teamed up with educators to make their games user-friendly for the classroom. **TeachwithPortals.com** provides several lesson plans in physics, geometry, language arts and chemistry. Valve has also provided teachers with a puzzle-maker for *Portal 2* which gives teachers more control over the design of the game and lets them (or even students) create their own puzzles for students to solve.

Quest Atlantis (Sasha Barab and Melissa Gresalfi)
http://atlantisremixed.org

Quest Atlantis is an international online 3D game for children from 9 to 15 that features scientific inquiry. It has many different units that encourage children to take on the roles of scientists, doctors, reporters and statisticians. The Ander City statistics unit explores data sets and how they can be used deceitfully. Another unit explores ethics and language arts by using the book Frankenstein as a platform; students have to decide whether to use a scientist's living creation as a test subject for a cure that could save the city's citizens. Most of the units inspire social action, such as the Taiga Water Quality unit. As expressed on their website, "Taiga best exemplifies the potential for connecting content with context by supporting students' experience of the consequentiality of their actions. For example, after students have begun to learn about potential causes of the fish demise in Taiga Park, they are asked to make a recommendation about how to resolve the issue. In making this decision, students have to consider their conceptual tools (i.e. understanding eutrophication, erosion, and overfishing) in order to make a recommendation about what to do (i.e. stop the indigenous people from farming, tell the loggers they can no longer cut trees in the park, or shut down the game fishing company)."

River City (Harvard University)
http://muve.gse.harvard.edu/rivercityproject

River City is a 3D virtual environment that aims to facilitate 21st century skills and scientific inquiry. As explained on the website, "*River City* Curriculum is interdisciplinary in scope, spanning the domains of ecology, health, biology, chemistry, and earth science, as well as history. Three diseases simultaneously affect health in *River City*, based on historical, social, and geographical content. As students explore these diseases, they learn how disease is spread and how human interactions can have effects far from the initial site. This situation allows students to experience the realities of identifying a problem, investigating it, and delineating the multiple causes that underlie a complex phenomenon. Students follow multiple threads that potentially lead to very different hypotheses and experiments. This helps refute the common belief that there is one right answer to any science experiment." The game is a 17-hour course that is designed to replace existing class lectures.

Roller Coaster Tycoon (Chris Sawyer Productions)
http://www.rollercoastertycoon.com

Roller Coaster Tycoon is a commercial construction and management game where players design roller coasters and also the theme park they exist in. Players have to overcome and utilize different forces like momentum and gravity. The player's rides must carefully choose the direction, loops (corkscrews, vertical loops, zero gravity rolls), and height of their rides to meet their customers' preferences. If they are careless, the rides can crash and cause injuries and the popularity of their parks will plummet.

SimCity (Maxis)
http://www.simcity.com

Sim City is a city-building simulation game that allows players to build and design a city. There is no specific goal to achieve; instead, players must manage their commercial, industrial, and residential zones while expanding their cities and nurturing their economies. Players must simultaneously keep an eye on crime levels, power supply, population, and traffic congestion. Natural disasters and power plant accidents may interrupt their efforts. Players are also evaluated by the citizens depending on the production of public goods and tax rates.

Spore (Maxis)
http://www.spore.com

Spore is a simulation/strategy game where the player develops a species as it undergoes evolution. The player starts with a microscopic organism and eventually develops it into a complex creature with social and intellectual features. The player must develop his species' assets to survive the changing environment. *Spore* is also famous for its community aspect as players can upload their own creations to Youtube and to *Sporecast*.

Supercharged! (MIT Education Arcade)
http://educationarcade.org/supercharged

Supercharged! is a 3D simulation game designed to help introductory physics students develop intuitive understandings of electrostatics. As the website explains, "The game places students in a three dimensional environment where they must navigate a spaceship by controlling the electric charge of the ship, placing charged particles around the space. Students must carefully plan their trajectory through each level by tracing the field lines that emanate from charged objects, and in the process of doing so, develop a more hands on understanding of how charged particles interact." The idea of the game is that "by representing complex scientific content through tangible, experienced nontextually-mediated representations, simulated worlds may also engage reluctant learners in the study of science."

The Pandora Project (Harvard University)
http://edgaps.org/gaps/projects/past-projects/pandora-project/

The Pandora Project was a role-playing game in which students developed islands of expertise in the science and ethics of xenotransplantation by engaging in the practices of professional mediators. As explained on the website, "Players take on stakeholder roles in groups of three and spend several class periods conducting a conflict assessment, using internet links in the game to research their positions on xenotransplantation and the positions of the other stakeholders. They gather information on genetics, epidemiology, and cell biology they need to argue for their position. Based on their research, each stakeholder group prioritizes the issues in the dispute and the various options for each one. Using these priorities, players divide into groups, with each player representing a stakeholder in one of three separate negotiations. The negotiations take place over several hours, and the game ends with the same kind of debriefing that takes place in a negotiation practicum."

The Sims (Electronic Arts)

The Sims is a commercial life-strategy simulation game where players can create Sims (virtual people) and guide them through their lives. Sims will need to get jobs to bring in income, balance relationships with neighbors and family, and also fulfill their dreams. Players manage their Sim's bills while also directing them to obtain skills, like playing guitar or logic, which help obtain promotions at work. *The Sims* also has an impressive architecture tool, and players can design the houses that Sims live in from the ground up and can create entire communities.

UVa Bay Game (University of Virginia)
http://www.virginia.edu/baygame/

"*The UVa Bay Game* is a large-scale participatory simulation based on the Chesapeake Bay watershed. The game allows players to take the roles of stakeholders, such as farmers, developer, watermen, and local policy-makers, make decisions about their livelihoods or regulatory authority; and see the impacts of their decisions on their own personal finances, the regional economy, and watershed health. It is an adaptable educational and learning tool for raising awareness about watershed stewardship anywhere in the world; a tool for exploring and testing policy choices; and a tool for evaluating new products and services."

I had the pleasure of speaking with Mr. Jeffrey Plank, the Associate Vice President for Research. The *UVa Bay Game* was developed by multiple faculty members across multiple disciplines who saw the need for a tool that would include all the information and interconnections about watersheds to create system-thinking and create motivation for social impact. He explained how that the simulation revolutionized how they taught about watersheds and allowed players to act as live agents. They are currently working on creating a generalized template so the game can be developed for any watershed and be open source to other universities. They have had great success with *The UVa Bay Game,* and research and information is available on their website.

World of Goo (2D Boy)
http://www.worldofgoo.com/

World of Goo is a commercial physics-based puzzle game. Players must build bridges, towers, and other structures using balls of goo and balloons. The structures must overcome forces working against them, such as gravity, while avoiding obstacles like other structures, hills, and spikes.