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Supporting STEM Learning With Gaming Technologies: Principles for Effective Design

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Abstract

In this paper, methods and models for the design of educational interventions and usable systems are presented and synthesized. The purpose is to suplliment the design process with educational considerations and discern design principles for the development of serious STEM games. This synthesis can contribute to the design of the next generation of technologically enhanced learning environments.

Introduction

Gaming has the potential to motivate students, while situating important concepts and techniques in real-world contexts, and providing opportunities for learning through play and collaborative sense-making. These are precisely the types of learning environments that lead to deeper, richer, and more powerful learning experiences (Collins, Brown, & Holum, 1991; Scardemelia & Bereiter, 2002; White, 1993; Vygotsky, 1978). Video gaming and other integrative educational technologies are likely the future of education (Borgman et. al, 2008), but are currently in need of design principles and effective assessment practices (Computing Research Association, 2005). Games designed by researchers are theoretically grounded, but usually designed for research purposes and therefore have problems transferring into mainstream classrooms. On the other hand, games designed for mainstream use often prioritize fun over actual science content (Drake, 2012).

Early research in educational gaming was largely influenced by developmental and cognitive theories of learning. Though this pioneering research showed promising results, the state of technology did not support easy implementation or widespread acceptance. Today, the proliferation of technological innovation and the growth of Human Computer Interaction (HCI) and software engineering have created a generation of designers interested in exploring how technology can refine and support thinking and learning.

There are various methods for developing informed and usable systems, but they will not be the focus of this paper. There are books designed to intoduce developers to usability techniques and models of human centered design (e.g., Nielson, 1993; Rosson & Carroll, 2002). What is less available for designers interested in developing educational gaming technologies are the concepts and practices that educational researchers and practioners would value and look for in serious STEM games.

The aim of this paper is to provide designers with supplimental information centering on educational considerations relevant at each point in the design process. This information includes educationally informed design principals. We begin by presenting our previous work and experience with educational technologies. We then present methods for the design of effective interventions and systems. These methods, along with previous work and experience, are synthesized as a means to discern design principles, to guide the design of educational gaming technology. We conclude the paper with a discussion of the limitations of generalized principles, but suggest that it is a first step towards bridging the gap between theory, design, and educational practice.

Prior research

The authors of this paper have strong ties to the fields of information sciences, computer science, and education. They also have a long history of developing innovative learning tools as part of the ThinkerTools research group. Their previous work with intelligent advising systems, serious games, and related curricula are used as exemplars for technological innovation in the teaching and learning of science (Computing Research Association, 2005; Donovan & Bransford, 2005; Duschl, Schweingruber, & Shouse, 2007).

The focus of the first author's dissertation was on discerning core collaborative capabilities and prototyping tools to support development of these capabilities in children during collaborative inquiry projects (Borge, 2007). Her subsequent work has extended this research to support the design of curriculum and technology in higher education to support group cognition during long-term design projects (Carroll & Borge, 2007; Borge & Carroll, 2010; Caroll Borge, Ganoe, & Jiang, 2010).

The focus in the second author's doctoral dissertation was on designing computer games and microworlds that could provide new ways of promoting conceptual change in students' understanding of Newtonian mechanics. Initially this work took the form of a sequence of serious educational games (White, 1981; 1983; 1984) and later evolved into a more sophisticated software environment, called ThinkerTools, that let students create their own games and even change the laws of physics (White, 1993; White & Frederiksen, 1998). The design goal was to enable students to develop increasingly sophisticated conceptual models for reasoning about how forces affect the motion of objects, while also learning about the processes of scientific inquiry and modelling. This influencial work represents some of the first studies on serious games in education.

Our subsequent work focused on teaching students more broadly about their own thinking and learning processes that are needed for collaborative scientific inquiry. The system we developed was called Inquiry Island and evolved into the Web of Inquiry (Eslinger, White & Frederiksen, 2002; Shimoda, White, & Frederiksen, 2002; White, Shimoda, & Frederiksen, 1999). This system was comprised of intelligent advisors informed by qualitative conceptual models of the inquiry process. These advisors used student input to provide them with appropriate advice, assistance, and concrete examples to guide their ability to engage in authentic inquiry and control their own learning processes. The advisors focused on supporting cognitive, metacognitive, and sociocognitive activity.

In pursuing this line of research, we have taken a skeptical attitude toward conventional ways of teaching. We have asked, what happens if you abandon the conventional methods of teaching science and conventional views of what young students of various ages are capable of learning (Brown, Metz, & Campione, 1996; Metz, 1995)? What happens if you come at it conceptually from a cognitive and social point of view, using technology as a tool to represent and teach in new ways? Throughout our work, we have been seeking ways for teaching science that will enable students to understand new things in the future, and that will also build their understanding of themselves as problem solvers and learners – that is, develop their metacognitive expertise (Brown, 1984; Campione, 1987).

Much of our work has been conducted in urban settings with a high percentage of underrepresented and disadvantaged students, and findings from our work have raised the bar for science education. Our approach has always been to provide all students with cognitively rich environments and use technology as a means to model, support, and guide learning while allowing students to play with and manipulate models of physical and psychological phenomena. At each stage in our work, we have discovered that children are capable of mastering knowledge and processes for learning that we thought were going to be very challenging for them. This led us to raise progressively our expectations for what children can learn and do and the thinking processes technology can support. As a result, the technology and related curriculum we have developed and tested have supported a movement to shift K-12 science instruction from rote memorization tasks to a model of inquiry practice. Our findings also support current views that gaming and intelligent learning environments have enormous educational potential for diverse learners (White & Frederiksen, 2007). The prospect of a generation of designers interested in methods for developing new, sophisticated, and perhaps even unconventional learning environments is exciting.

Methods and models for effective design

The design of educational interventions

In order to guide the design of effective educational interventions, their implementation, and evaluation, it is necessary to gather sufficent information to devise a theory of the task, a theory of the development of competence, and a theory of instruction (Brown, 1984). Each theory focuses on developing conceptual models to inform the design process and as such should be informed by theories of learning, development, and educational practice. A theory of the task refers to a theory of what the task looks like and the processes entailed as part of its completion; it is an understanding of the major goals of the activity that is the focus of development. For serious STEM games, the task refers to the core concepts and processes of a STEM domain. A theory of the development of competence is an articulation of (1) what it would look like to demonstrate possesion of the required knowledge and procedures and (2) how one develops competence over time. A theory of instruction refers to an articulation of the instructional methods and strategies needed to help students develop competence.

The design of usable systems

Scenario based development (SBD) is a systematic approach to human centered design that promotes active synthesis and reflection throughout the development process (Rosson & Carroll, 2002). The three central components to SBD are scenarios, claims, and Human Computer Interaction (HCI) knowledge (see figure 1). SBD requires designers to create scenarios specific to each

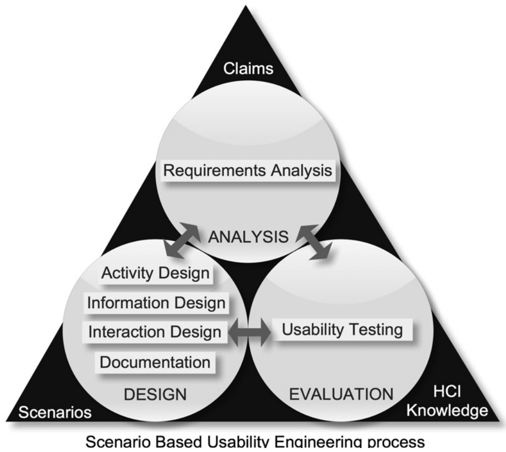

Figure 1: A diagram illustrating the Scenario Based Development frame-work from the Usability Case Library (see Overview/Framework/Components in http://ucs.ist.psu.edu).

phase of the HCI design process that synthesize data and articulate ideas and claims to stakeholders. These scenarios are essentially low-fidelity models of the design problem or proposed design solutions created by the designer. Designers share these scenarios with appropriate stakeholders as a means to identify problems and revise ideas as necessary. This process alleviates many of the challenges inherent in the design of systems (Carroll 2000).

SBD breaks down the product life cycle into three stages with iterative cycles of research, analysis, and artifact creation within each. The three stages include (1) analysis, (2) design, and (3) formative evaluation (for concrete examples of all the phases contained within each stage see ucs.ist.psu.edu). Each stage seeds ideas for the next, so it is important that designers get feedback from stakeholders to ensure that data has been properly interpreted in order to make valid claims, evaluate design trade-offs, and propose solutions that work.

Synthesizing methods to propose principles for effective educational gaming design

The design of serious games must be informed by educational considerations so as to increase the likelihood of technology transfer. Serious STEM games need to focus on STEM content or methods: the types of knowledge required for expertise or ways to promote the development of expertise (Collins et al., 1991). However, models or principals to guide the design or assessment of serious STEM games is lacking (Computing Research Association, 2005). For this reason, we propose discerning principals for the design of serious STEM games by formally synthesizing methods and models from highly regarded work in educational psychology and usability engineering. To a large extent this is what we have done as part of our prior work.

This section is organized according to the three stages of SBD (1) analysis, (2) design, and (3) evaluation. For the purposes of this paper, we only focus on phases within the three stages of the product lifecycle that can be further informed by developing STEM domain theories: the theory of the task, the theory of competence, and the theory of instruction. This synthesis of methods is not intended as a means to replace the methods and techniques proposed by the SBD process, but rather to serve as a supplement for designers taking on the challenge of developing serious educational STEM games. Where possible, examples are provided from our prior research and experience in creating successful educational environments.

1. Analysis

In SBD, the focus of the analysis phase is on requirements for the system. During this phase, designers use HCI methods to try to understand the activity system to which the technological product will belong (Nardi, 1995). They plan out and implement ways to gather and analyze information. Information can be gathered through various methods, i.e., interviews with stakeholders, field observations, and ongoing negotiation of ideas with clients, potential users, and programmers. During this phase serious STEM game designers should place emphasis on gathering information about accepted ideas and practices of STEM domain experts, educators, and researchers. This is important because educational researchers have demonstrated the large extent to which people, regardless of age, hold misconceptions about math and science concepts. In order to ensure that designers do not perpetuate these misconceptions they should be mindful of the following.

Ensure that the game embodies conceptual models of the task that coincide with those accepted by associated communities of practice

An important aspect of the process of determining requirements for the system is to devise a theory of the STEM domain task that the game centers on. There is a great deal of information available to game designers about STEM related disciplines. There are expert models of the core concepts and capabilities of differing domains. There is also a great deal of research on thinking processes that need to be developed to support STEM learning. For example, models of science inquiry practice informed the design of The Web of Inquiry: a complex system to support children's ability to understand and engage in authentic science inquiry (Herrenkohl, Tasker, & White, 2010; White, Shimoda, & Frederiksen, 1999).

Designers working with complex content areas should work with domain experts to create conceptual models and scenarios to illustrate their shared understanding of core concepts and methods of a domain or common problems that the game will address. There are also many teachers who are experts in progressive and innovative teaching practice and could serve as subjects of observation for a task analysis of progressive instructional methods.

This information can be used to develop rich problem scenarios, such as narratives that illustrate current knowledge and accepted practices of a domain from different stakeholder perspectives. For example, one scenario could focus on how experts apply a science principle in practice, while another scenario could focus on students naïve misconception of that science principle, and a third scenario could focus on how teachers work to help students recognize and correct that misconception. These artifacts should be shared with appropriate experts as a means of identifying false assumptions and necessary modifications in order to form initial root concepts and instructional goals of the game.

Use information gathered from requirements to develop a theory of competence from which to further articulate learning goals

A theory of competence clearly expresses the intended learning outcomes of a game by detailing expert performance and what it would mean to masterfully carry out a task. For example, scientists are experts at carrying out inquiry. They follow systematic, empirical methods. Their questions are grounded in theory, they propose testable, competing hypotheses, and their methods are replicable. They not only collect and analyze data, but also synthesize and interpret it in order to make predictions about the world. These expert characteristics were used to inform our theory of competent inquiry practice for the Web of Inquiry and articulate the learning objectives and assessments for modules in the system.

2. Design

The design stage includes four phases of design reasoning: activity, information, interaction, and documentation design. Here, we focus on educational considerations during activity, information, and interaction design, since they focus on understanding and structuring the STEM domain task rather than learning to use the system. Designers should be aware of underlying educational theories and practices in order to explore ways to organize, represent, and support concepts and activities in the system.

Use the conceptual models developd during the requirments phase to guide how information and activities are presented and organized in the system

Once a theory of the task is developed and negotiated with domain experts, it can be used as a means to guide design. The model can serve to identify the types of information that need to exist as part of the system and devise a plan for how this information should be organized and accessed by the user. For example, we developed a system of intelligent agents with distributed expertise that could work together to support students' thinking as they engaged in inquiry science. A model of inquiry guided the order in which information and advice was presented by the agents in the system.

Find creative and systematic ways to simplify complex concepts into manageable information pieces that students can apply

In order to develop a theory of instruction, designers need to think about the progression of concepts and activities that will occur in the system. In past work, we have deconstructed complex STEM processes and systems in an attempt to simplify them. For example, Inquiry Island and The Web of Inquiry used a top down approach to organizing scientific concepts. Information would be presented as general statements with increasing detail and concrete examples available to students who desired further clarification. Similar methods have been proposed whereby complex ideas are deconstructed and modeled to students as part learning activity (Borge & Carroll, 2010; Brown & Palincsar, 1985; White & Frederiksen, 1990). These concepts supported students' inquiry during actual practice.

Ensure that players have opportunities to apply concepts and methods and engage in active knowledge construction

At it's core we maintain that educational gaming must create learning environments in line with constructivist learning theory: learning environments where individuals become active participants, make sense of information in the system, manipulate objects, and negotiate understanding with others. Through this type of activity the players can actively work to develop expertise in the domain to which the game belongs. Ideally the player should be able to create artifacts or objects as part of the digital world as a means of expressing what they have learned (Collins et al., 1991; Lave & Wenger, 1991; Scardemelia & Bereiter, 2002). Creating artifacts in the system could serve as a means for the player to articulate their understanding and further enrich the digital environment by providing new objects for future players to make sense of or manipulate.

Serious gaming should be fun, but also make sense within the scope of the domain

One fallacy of educational game design is the development of an environment where the domain content is a peripheral component of the game: a rote task to complete befor you have "fun" (Klopfer et. al, 2009). Requiring students to define a scientific concept before being allowed to paint or collect a prize is one such example. These types of activity design may not support refinement of students' mental models of the domain and will likely fail to engage the learners over time (Baker 2008). Too many unrelated bells and whistles can also distract players and make learning game components more difficult (Carroll, 1990). The game in and of itself should serve as a means for the player to develop and revise their understanding of core domain principles. For this reason, irrelevant games may frustrate, bore, or confuse the learner. The game needs to be situated within authentic domain problems or contexts so learners can develop situated knowledge and practice applying core concepts and methods in ways that emulate expert practice (Collins et al, 1991). Such contexts can include engaging in serious scientific inquiry (White & Frederiksen, 1998; 2007).

Engage learners by focusing on common problems or misconceptions in the domain

Games should allow for students to be motivated by natural curiousity and a desire to successfully overcome obstacles. Problem solving is inherently motivational (Mayer, 1998) and through play individuals will likely exert added effort to learn (Dewey, 1910). The challenge for game designers is to create interesting and authentic problems for players to solve. Luckily for game designers interested STEM domains, there are decades of research on common problems and misconceptions related to math, science, and technology, i.e., evolution, force and motion, data representation. Creating games that center on identifying and exploring students misconceptions can both engage learners and help them to confront inconsistencies between their own mental models and those of domain experts (White, 1993).

Devise learning progressions by gradually building to increasing levels of complexity in the game and required understanding by the player

In order to provide learners with foundations for more complex learning, designers should devise ways to build understanding of a complex problem or domain as a process of gradual mental model refinement over time (White & Frederiksen, 1990). This can be accomplished by providing students with an initial conceptual model and then changing the perspective, order, or degree of elaboration of the model articulated as part of the game. In this way the learners understanding can evolve gradually.

Facilitate the use of problem-solving heuristics and help seeking

It is important that a game be sufficiently challenging, but in order to stay engaged, the player needs to have some means by which to solve new challenges. Gradually building to increasing levels of complexity can facilitate the use of problem solving heuristics, but other forms of interaction and help are also important. These include, providing access to additional learning resources, opportunities to apply knowledge from previous experience, and providing feedback on performance.

Additional learning content could be embedded in the game as a means of helping the player to accomplish a goal or correct a problem by engaging in active inquiry. For example, games could contain links to information that could help players understand why they failed an aspect of the game. Games could also provide examples of common mistakes players make and explain the science behind aspects of the game. These would not necessarily be required aspects of the game, but supplementary materials embedded within different or even secret parts of the game. Finding ways to provide players with access to secret content may provide them with motivation to engage in inquiry by testing how differing moves in a game will affect gaming outcomes.

Find ways to promote transfer of gameplay to key domain problems, inquiry, or collaborative discussion

Games can serve as a bridge between knowledge development, application, inquiry, and discourse by allowing players to learn about concepts through play, manipulation of domain phenomena, and identification of domain problems. In this way, games can serve as benchmarks for learning content (diSessa & Minstrell, 1998); they can present learners with key principles of a domain in interesting and engaging ways and motivate learners to develop more knowledge through inquiry.

In order to promote continued learning, games could actively support inquiry. For example, the concepts students learned as part of interacting with ThinkerTools Force and Motion microworlds had real world application. Therefore, we developed related curricula where students could create inquiry projects to test these concepts in the real world, thereby developing their ability to think about and evaluate the underlying concepts and laws empirically.

Games can also provide opportunities for collaborative discussion. For example, ill-structured problems are commonly used as a means to develop collaborative skills. These are problems with no correct answer, or path to solution, where players must share information, figure out how to solve the problem, and evaluate potential trade-offs of differing decisions. They are the type of problems best accomplished through collaboration, which motivate students to seek additional information from the game or their peers. For example, complex, online multiplayer games, like World of Warcraft, are ill-structured problem solving games. World of Warcraft does an excellent job at providing users with opportunities to engage in collaborative problem solving, develop collaborative skills, and motivate their learning even though it was not intended to be an educational game (Nardi & Harris, 2006).

3. System evaluation

In order to engage in system evaluation designers need devise an evaluation plan, get access to students, and then implement and assess the system. Once a set plan is in place that includes the methods and materials for data collection, implementaion, and evaluation of the system, designers can begin testing the system. During system evaluation the designer must reflect on all the previous design phases. They must evaluate the traditional usability and utility of the game given the theory of the task, the theory of competence, the theory of instruction, as well as the specific demographic population for which the game was intended. Institutional expectations, rules, and constraints, as well as misconceptions of children's and teacher's time and abilities can pose problems during this stage. There are steps designers can take to minimize these problems and are described as follows.

Measure traditional usability before measuring learning gains, preferably in informal learning environments

Once a prototype is available, it should be tested to assess the traditional usability of the game: can players easily learn game features, does the game perform well during real use, is the game fun and engaging. During initial pilots, it is uncertain to what extent the game will perform as expected. Many teachers have difficulty dealing with this type of uncertainty given their many demands. For this reason, it is a good idea to conduct initial piloting of new educational software in informal environments such as afterschool programs, summer camps, or in the lab. These environments have fewer restrictions on curriculum and student time. They are also more flexible than formal environments as there are no required instructional standards placed on teachers or students in these settings.

Most importantly, they allow for designers to get quick feedback on whether the system meets the needs of younger users. Children may not have the same metaphorical understanding of user interface designs as adults and developmental differences may impact the effectiveness of different interfaces and activities (Najjar, 1998; Nielsen, 2010)

Build relationships with individuals and organizations to facilitate access to testing cites

It can be difficult for designers to get access to real students as rules have rightly been put into place to protect students from harm. For example, many educational environments, formal and informal have requirements for special training and clearances of any adults who work with children to ensure that individuals with criminal records or history of child abuse are not allowed near students. School districts may also have established procedures for conducting research in classroom settings to prevent interference with required learning.

A common approach used by many educational researchers is to build partnerships. Relationships are developed with individual teachers or heads of educational programs who can provide researchers with insights into the process and help to promote the inherent value of the intervention. In this way researchers can work with these partners to figure out what they need to do to be allowed the privilege of working with teachers and students. This privilege is often extended based on reputation so it is important to find ways to balance the needs of teachers and students with those of the research in order to maintain a good relationship with those participating. This will facilitate future collaboration.

Use initial theory of competence to devise assessments to measure learning outcomes.

Within the HCI community the concept of usability has expanded to include utility: the extent to which a technology fulfills, extends, or falls short of the intended goals of the system (Carroll, 2009). One of the most important goals of an educational game is that it leads to learning or developmental gains, particularly in classroom settings. In order to test the utility of a STEM game, assessments need to be developed based on the theory of competence identified during the requirements process.

In the analysis section, we discussed how expert characteristics and processes were used to guide the learning objectives for our inquiry science software and our conceptual model of scientific inquiry; this was our theory of competence. This theory served as the foundation for inquiry science assessments that we developed and then tested for reliability and validity (White & Frederiksen, 1998, 2007). These assessments were then utilized as part of a multi-school, multi-classroom study to assess the educational and developmental utility of the system we designed: strengths and weaknesses. Pre and post assessments were double blindly scored using reliable coding rubrics. These pre and post assessments were supplemented by looking at the content of what students communicated during classroom discussions and in the system.

Discussion

One could question the extent to which generalized principles would be of use to game designers, but given that these principles are a synthesis of cross disciplinary work, we argue that they can also serve as a means to begin the process of bridging communities of practice. The development of effective technological tools will require collaboration between cross disciplinary teams. Expert designers have years of technical experience and know far more about aspects of game design than those covered by these principles. However, as more designers become interested in creating games to enhance comprehension, expertise, or interest in STEM domains, it is necessary that they suppliment their technical expertise with knowledge of educational theory and practice. In this way they can learn the "language" of educational researchers and practioners and collaborate with them more effectively. As technology becomes an increasingly pervasive and necessary part of our culture, it is also likely that educational researchers and practitioners may join the ranks of serious game designers and they should also introduce themselves to important design methods and models. For these reasons it is necessary to bridge the divide between these communities. This was one of the main objectives of this paper, to introduce all of these participants to the many central ideas that connect them. We hope to see a proliferation of collaborative work between these communities so they may work together to create the next generation of technologically enhanced learning environments.

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