The Use of Simulations for Building Effective Discovery Learning Environments

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***Abstract* — This paper discusses the role of simulations in discovery learning environments and builds a framework for designing, implementing, and evaluating these environments. Examples and principles are drawn from current research in this area and my research is discussed in light of the proposed framework.**

I. Introduction

"CHILDREN construct their own knowledge through experience" [2,16]. The constructivist approach to education centers on this claim. Various tools can enhance these experiences with which the learner constructs his or her own knowledge. Vygotsky maintains this notion of tools which could "enrich and broaden both the scope of activity and the scope of thinking of the child" [1,17]. The personal computer is a versatile tool that can present a wide variety of learning experiences. In particular, it enables a person to experience or witness a representation of something that might not otherwise be readily observable. This makes computer-based simulations a powerful tool for learning.

In the context of this paper, a simulation is a representation of a dynamic process. In a simulation-based learning environment, "the main task of the learner is to infer the characteristics of the model underlying the simulation" [1]. In other words, the learner is provided with an experience that he or she must attempt to explain. This is generally done through hypothesis generation and testing, both of which are made possible through the simulation. This specific form of constructivist learning is called scientific discovery learning.

The process of scientific discovery learning involves learning from an iterative cycle of planning, executing, and evaluating. The exact steps of this cycle have been broken down in different ways by various researchers. For example, Friedler et. al. list these steps as "(a) define a scientific problem; (b) state a hypothesis; (c) design an experiment; (d) observe, collect , analyze, and interpret data; (e) apply the results; and (f) make predictions on the basis of results" [1,18]. White and Frederiksen propose an Inquiry Cycle in which learners "(a) develop their research question, (b) generate hypotheses, (c) design an investigation, (d) record and analyze their data, (e) create a model, and (f) evaluate the utility and limitations of their model, as well as their research processes, and identify new questions to investigate" [3]. Finally, de Jong and van Joolingen break down scientific discovery learning into a cycle of "hypothesis generation, design of experiments, interpretation of data, and regulation of learning" [1].

Regardless of the specifics of how this cycle is broken down, it is clear that the simulation learning environment must be carefully designed to allow this discovery process to occur. Instead of the simulation explicitly teaching the student[1] what he or she needs to know, it provides an environment where the student can explore and test hypotheses and discover for him or herself.

II. Design

In this section, I propose three goals for designing a simulation-based discovery learning environment. First, it must support the acquisition of the domain knowledge necessary for understanding the model that drives the simulation. Second, it must support the learner in going through the discovery learning process and attempt to correct common misconceptions and mistakes. Finally the environment must provide metacognitive support in order to develop the learners' ability to plan and monitor his or her own learning.

A. Domain knowledge support

The first design goal of a simulation-based learning environment is to provide the student with the means to learn the domain knowledge. The simulation plays the role of bridging the gap between the "real world" and a formalized model representing a subset of this world. A balance must be found in making the simulation accurate enough to convey correct domain knowledge, but abstract and simple enough as to successfully bridge this gap and help the student understand concepts that might not be easily grasped in a completely accurate model of the world.

The environment must also scaffold the student with the prior knowledge necessary for setting off on the discovery learning process. Although the main goal is for the student to discover and construct the knowledge on his or her own, some amount of domain knowledge needs to be provided independent of the simulation.

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[1] The words *learner* and *student* are used interchangeably.

B. *Discovery learning support*

In a quick overview of results from studies on the use of simulations in computer-based education, de Jong and van Joolingen observe that, "the general conclusion that emerges from these studies is that there is no clear and univocal outcome in favor of simulations" [1]. Merely providing a simulation environment that fosters constructivist learning of a given domain is not enough. Often times, learners are novices not only in the knowledge domain but also in the scientific discovery learning process.

Simulations must support learners in overcoming problems that learners face in discovery learning [1]. The issues that must be addressed in the design of these systems goes beyond the crafting of the simulation. The system must provide a way to address problems that learners frequently encounter in discovery learning. de Jong and van Joolingen extensively examine the literature for specific problems that learners encounter in discovery learning. I will give a few examples from each one of their phases of the discovery learning process:

Hypothesis generation. Learners avoid hypotheses that have a high chance of being rejected or they may not even understand what a hypothesis should look like.

Design of experiments. Confirmation bias leads learners to only acquire data that confirms a hypothesis. Learners may also produce inconclusive experiments by changing too many variables.

Interpretation of data. Learners often misinterpret data, allowing their hypothesis to influence the interpretation. Also, learners often find it difficult to interpret graphs.

Regulation of discovery learning. Learners may not successfully plan their experiments, using a random strategy and making local decisions without understanding the larger picture.

A good example of designing a learning environment that supports students in overcoming their problems in discovery learning is White's Inquiry Island software [3,5]. In Inquiry Island, there are task advisors which serve as mentors for the student. Each task advisor assists the student with tasks associated with a specific step of the inquiry cycle. These advisors help the student overcome some of the common problems mentioned above. They also provide students with a defined structure to follow as they progress through the inquiry cycle.

C. *Metacognitive support*

Although some of the metacognitive aspects of discovery learning are incorporated into the discovery learning cycle as described above (e.g. *regulation of learning*), the importance of developing and encouraging the use of these skills warrants looking at metacognitive support as the third design goal of a simulation-based learning environment. "Metacognitive expertise is needed in developing knowledge through inquiry" [3]. In particular, metacognitive knowledge and skills are important for preparing the student for future learning [14].

By performing regulatory monitoring and planning tasks, the learner can think critically about his or her learning progress and make necessary adjustments. One way that the learning environment can provide support for the development and practice of these skills is to model them to the learner in the form of an agent's behavior. Studies have shown that by modeling this behavior in a pedagogical agent present in the learning environment, the learner picks up on these behaviors, incorporates them into their own learning strategies, and as a result, exhibit deeper understanding of the given domain and an enhanced ability to apply these acquired skills to future learning [4].

A second way to provide this support is to allow the students to take an active role in tailoring the discovery learning support to their own needs. Taking the types of support discussed in the previous session to the next level, the learner is now responsible for understanding how and when this support is most effective. An example of this is an extension of Inquiry Island called SCI-WISE [5]. One of the key features of SCI-WISE is that the student has the opportunity to alter the behavior and presence of each advisor. For example, the student can choose to change the amount of initiative that the "Helen Hypothesizer" advisor takes in offering assistance, or the student can disable this advisor altogether. Practicing this task helps students understand how they can help themselves learn.

III. Implementation

A. *Implementing the design principles*

The implementation of a simulation-based discovery learning environment should seek to use computer technology in order to best meet the previously mentioned design goals.

First, the simulation must be implemented in a way that allows the student to infer the underlying model driving the system. This means that the right balance must be found between a complex, accurate representation of the conceptual domain and a simple, abstract representation of the same domain. Additionally, the learner must have some amount of prior knowledge in the domain in order to successfully proceed through the discovery learning process. Though this knowledge may come from classroom instruction or other course materials, it is often necessary to provide domain knowledge resources in the system. The presentation of these resources can make a difference in their effectiveness. Various studies have shown the advantages and disadvantages of different types of resources (e.g. hypertext and hypermedia), the timing of the resources (e.g. presented before interacting with the simulation or at the exact moment when that information is relevant), and the availability of the resources (e.g. available upon request by the learner or upon the system determining that the learner needs the information) [1]. A student model may be required to maintain the knowledge and misconceptions of the student and effectively tailor the domain knowledge support with the optimal content at the optimal time.

Another consideration is that the technology (both the hardware and software) should not interfere with the presentation of the simulation. It should be adequately seamless and realistic to the student. A good example of this is the use of Thinking Tags for the Participatory Simulations Project [2]. In this extreme example, participatory simulations take the student out from the typical keyboard, mouse and monitor computer learning environment, and allow the students to actually become a part of the simulation. However, in a more traditional computer-based system, it is still important that the technology not get in the way of the student trying to understand the underlying model of the simulation.

As already mentioned, the simulation-based system must also support the learner in his or her discovery learning process. One way to implement this is to provide the learner with useful tools within the simulation environment that support the various stages of the discovery learning cycle. Graphing tools, hypothesis notebooks, and adaptive and dynamic hints are examples of tools that have been implemented and proven useful in such environments [1].

Another way to provide this support is the use of pedagogical agents. Inquiry Island uses artificial agents in the form of advisors to assist the student as necessary. These agents maintain a set of beliefs and use a forward-reasoning, inference engine to make decisions [5]. This multi-agent implementation allows interactions from one advisor to another in addition to the interactions between the agent and the student. The presence of these agents creates a collaborative learning environment (which is an entire topic that can be explored elsewhere), adding to the constructivist nature of the simulation-based learning environment. To increase the effectiveness of these agents, many recent systems have incorporated *animated pedagogical agents*. These "embodied" agents have the advantage of communicating with the student in multiple modalities (speech, facial expressions, gestures, and motion), effectively increasing the bandwidth with which the agent can communicate with the student [6]. Animated agents also increase the ability for the computer-based system to engage and motivate the student, which is discussed below.

B. Engaging the learner

In a study from the mid-1980's, White introduced the notion of *games* to a simulation environment teaching Newtonian mechanics. These games were merely goal states for the student to reach in the simulation environment (i.e. maneuver a spaceship successfully to a location without hitting any walls) [1]. On a post-test, students who used a version of the simulation with games present outperformed students using an identical environment but without the notion of games included. Learner engagement and a heightened sense of involvement in the simulation environment enhance the learner's experience and encourage the discovery learning process. Two genres of implementing such involvement and immersion are video games and augmented reality.

1) Video games

Video games have been considered by some to be counterproductive to education [7]. Some educators, parents, and researchers believe that video games take away focus from classroom lessons and homework, stifle creative thinking, and promote unhealthy individualistic attitudes [8]. However, research into the effects of video games on behavior has shown that not all of the criticism is justified [9]. State of the art video games provide immersive and exciting virtual worlds for players. They use challenge, fantasy, and curiosity to engage attention. Interactive stories provide context, motivation, and clear goal structures for problem solving in the game environment. Researchers who study game behavior have determined that they place users in *flow states*, i.e., "state[s] of optimal experience, whereby a person is so engaged in activity that self-consciousness disappears, sense of time is lost, and the person engages in complex, goal-directed activity not for external rewards, but simply for the exhilaration of doing" [10].

Games such as SimCity and SimEarth are examples of popular simulation-based games with useful educational content [9]. However, there has been little formal evaluation of the pedagogical effects of these games. Moreover, gamers seldom take the time to try to understand the workings of the underlying simulation. Perhaps too goal-oriented, the gamer learns just enough about the system to be able to reach the next goal. To solve this problem, simulation-based video games for education must provide some amount of the supporting structure previously discussed in order to encourage the use and development of regulated, discovery learning and metacognitive skills. A proposition for such a system is in the last section of this paper.

2) Augmented reality (participatory simulations)

"Traditional" virtual reality systems have been used for entertainment, training, and even psychological programs [11]. Immersive virtual environments allow a person to experience and interact with an environment that he or she may not be able to experience in real life. One criticism against the heavy use of computers in the classroom or outside of school for educational purposes is that children should be learning from real-life experiences, and not from sitting in front of a computer for extended periods of time.

Computers have become increasingly ubiquitous, and its users are no longer confined to the traditional desktop computer. Furthermore, wireless networks allow for networked communication in a wide variety of environments. The idea of using augmented reality in education is to augment the real world with a simulated virtual reality. Such a system would possess the following desired properties [12]:

- Portability
- Social interactivity
- Context sensitivity
- Connectivity
- Individuality

In the Participatory Simulations Project, a group of high school biology students were given "Thinking Tags" that placed each student into the simulated "microworld" [2]. In this world, there was an outbreak of a contagious virus. The virus would spread by proximity in the simulation. This occurred in the real world when two students' Thinking Tags "met." With little guidance, students were charged with the task of learning who had the virus to begin with, understanding the dormancy period of the virus, and determining who was immune to the virus. The immersive and collaborative environment compelled the students to discuss strategies with one another and learn through discovery and inquiry with little help or prompting from the researchers. The strength of this simulated environment is that the computational devices themselves are unobtrusive. The students wearing these tags feel that they, and not the computer chip inside the tag, represent the agent in the simulation.

A more developed example of an augmented reality system implemented for educational use is Environment Detectives [11,12]. In this augmented reality experience, groups of students participate in a real-time simulation. The real-world environment includes streams, trees, and other natural elements found around the area (near the MIT campus). This environment is augmented with the simulation of a virtual environmental disaster (i.e. the river is being polluted). Handheld PDAs are central to this system, allowing students to move freely about the environment. The handheld computers are all connected to a wireless network. Equipped with communication capabilities, the PDAs provide a window into the virtual world. An on-screen map displays the students' current location. The students are formed into groups, and their goal is to determine the cause of the environmental disaster. As the students move around the environment, various multimedia are triggered and played on the PDA. The location and state of the virtual world determine what media is played. Additionally, students are able to take air and water readings and obtain geographical information. They can also interview various people, both real and virtual. By combining real-world and virtual-world data the teams of students seek to solve the problem.

Preliminary studies have shown the effectiveness of the augmented reality in promoting interaction and scientific inquiry. Colella writes, "New technology allows us to recast the notion of 'directly' interacting with a computationally simulated experience" [2].

IV. Evaluation

The evaluation of computer learning environments is essential for determining which designs and implementations are most effective. Most often, an iterative cycle of evaluation is performed. As noted by de Jong and van Joolingen, there are four types of papers that are found in the literature on discovery learning with computer simulations [1]. First, there are conceptual papers which discuss the theory behind such systems. Second, there are "engineering studies" that simply describe a learning environment. Third, there are studies that analyze empirical data gathered from log files and other sources. Finally there are studies which compare the simulation environment to expository teaching or to a similar but varied version of the same system.

Following these categories of studies, a typical system would ideally go through these four phases. Most importantly, the theoretical background must be there from the beginning, providing a sound pedagogical model to design the simulation environment around. After proposing and describing the learning environment, initial studies can be performed on a prototype system to evaluate the effectiveness each different component of the design. Finally, a complete study (or several different complete studies) that is carefully controlled to compare the full simulation-based learning environment against some baseline should be performed; all of these taking place as the system is iteratively updated and improved based on the results of the evaluations.

Perhaps the more difficult part of evaluating these systems is coming up with the best measure for comparing these systems. It is important to incorporate all three of the design goals already mentioned. The system should be evaluated on how well it teaches the domain knowledge as the driving model behind the simulation, how well it teaches and supports the students in their scientific discovery learning, and finally, how well it develops and fosters metacognitive development. Pre and post tests, as well as student performance while using the simulation environment can evaluate the system's effectiveness in accomplishing the first goal. The second goal, of supporting learners in the inquiry cycle, can be evaluated based on behavior logs, such as log files or "thinking aloud procedures." Qualitative analysis can be done on a case study basis. For example, with the Participatory Simulations Project pilot study, dialog excerpts coupled with the researchers' observations demonstrated the overall sense of collaborative scientific inquiry exhibited by the students. Finally, evaluating the metacognitive support can be performed by having the students participate in a transfer study, in order to evaluate the extent to which they learned how to learn and apply these skills to new domains. Other artifacts can be coded and evaluated as well. For example, in efforts to examine the metacognitive skills acquired from Inquiry Island, log notebooks were graded before and after the students' used the system and the difference was found to be significant. Finally, the Motivated Strategies for Learning Questionnaire (MSLQ) developed by Pintrich and DeGroot provides a quantitative method for evaluating of students' metacognitive development.

V. Conclusion and Research Directions

I have presented in this paper the current state of development in simulation-based discovery learning environments and have suggested a framework for the design, implementation, and evaluation of these systems. I have also suggested that the use of video games and/or augmented reality can enhance the learners' experience in using such a system.

One of my research goals is to develop a discovery learning environment which simulates an aquarium ecosystem. I will need to address the three goals I propose in my framework.

The ecosystem model driving the simulation must be implemented in a way that will best support the learner in inferring the underlying characteristics of the system. In order to motivate and engage students into the scientific discovery learning process, the simulation will be presented as a video game. Students will be faced with challenges to solve (e.g., determine the cause of dying fish) and have goals to meet (e.g., sustain a balanced aquarium with three fish for a sufficient time period). In order to promote self-regulated learning and the development of metacognitive skills, the learning-by-teaching paradigm will be employed through the use of a teachable agent [4]. The student will be challenged to teach the agent knowledge gathered from the simulation and together, they will solve each new problem. In the process of teaching the agent, the student will need to understand the workings of the underlying model, solving the problem of gamers only seeking to accomplish the next goal (as explained in section 3). Studying the differences in learning between when students use the simulation environment to learn and solve problems on their own versus when they are motivated to teach an agent and solve problems collaboratively will shed light on the effectiveness of combining a simulation game environment with the teachable agent framework.

Although simulation-based games are not new, there is an absence of game-based learning environments that combine modern video game technology with the pedagogical framework presented here in the form of discovery learning environments. The challenge of this research will be to perform this integration in a way that supports discovery learning, metacognitive development, and domain expertise all in the context of a simulation-based video game. Another challenge will be, formally and iteratively evaluating this system.

Technically, there exists the challenge of finding an appropriate platform for implementing such a system. There are many video game development platforms for game creation. However, none of these are designed with pedagogical concerns in mind. Therefore, the challenge will be not only in conceptually integrating a video game with a discovery learning environment, but finding the best way to actually implement this integration.

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*These first three papers are the assigned papers for this exam.