Simulation-Based Game Learning Environments: Building and Sustaining a Fish Tank

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Abstract

This paper describes an approach, where an exploration-based simulation environment for conducting and observing science experiments is combined with a game environment to provide a learning environment that supports deep learning with understanding and transfer. We describe the components of the learning environment, and the characteristics of the "inspectable" simulation to aid novice learners. Using a small experiment, we demonstrate the effectiveness of the simulation environment that includes active controls and a formative assessment scheme that aid monitoring and learning. The next steps are to extend this environment to a more extended "game" environment that includes a sequence of challenges to further motivate the student and expand their learning abilities.

1. Introduction

"Children construct their own knowledge through experiences gained by observing, exploring, and performing in the real world" [15]. The constructivist approach to education centers on this claim. A variety of tools can support the learner to construct his or her own knowledge in a way that leads to more efficient learning, provides motivation, and facilitates innovation. Vygotsky's social constructivism also supports the use of tools, which through scaffolding and providing directed pointers can "enrich and broaden both the scope of activity and the scope of thinking of the child" [16]. Given all of the advances in technology, the personal computer has become a versatile tool through which one can gain a wide variety of learning experiences. In particular, the integration of simulations, graphics, and animation enables users to experience and witness processes and procedures that might not otherwise be readily observable. This makes computer-based simulations a powerful tool for learning.

In simulation-based learning environments "the main task for the learner is to infer the characteristics of the model underlying the simulation" [1]. In other words, the simulation environment provides learners with observations and experiences that they must attempt to explain, assimilate, and combine with their existing knowledge. One way to achieve this is to get users to generate hypotheses from pre-defined goals, provide them with interactive controls to manipulate the simulation and other resources and scaffolds to help them run experiments to verify the hypotheses, and then apply them to answer questions and solve problems in different situations. Researchers have confirmed that "learning by exploration" in such simulation environments, i.e., learning with understanding and the ability to transfer to other problem solving situations [9], can lead to "effective learning" [10],.

Simulations used for teaching novices must differ significantly from the traditional simulation environments that are created and used for expert analysis. Simulations are often used by experts to create and study situations that would be very expensive or inappropriate to reproduce in the real world. The challenge in creating simulations to aid learning is to determine a proper design for a simulation environment that aids novices in learning the underlying models that govern the simulation domain.

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]. Simply putting students in front of a computer-based simulation is not sufficient to promote learning. The simulation must be situated in the context of a well-designed learning environment that supports appropriate discovery learning in the domain under study.

The goal of this paper is to design simulation-based game environments that provide an adequate "flow" to motivate the student and sustain their interest as they learn about complex dynamic processes. The simulation provides access to the required domain knowledge, and the game, as a wrapper around the simulation, provides a set of related challenge problems that the student must solve to learn about the domain. Section 2 provides a brief review of previous work performed in simulation and game environments. Section 3 then presents the design of the simulation-based learning environment in the context of building a fish tank, where the students have to ensure that their tank can sustain a number of fish over a period of time. Section 4 discusses the implementation of the system. Section 5 describes an experimental study we conducted in a 6th grade science classroom and the results. Sections 6, 7, and 8 present the discussion, directions for future work, and the conclusions of our work.

2. Simulations and games

In a study conducted in the mid-1980's, White introduced the idea of a *game structure* on a simulation environment for teaching Newtonian mechanics. These games merely defined the goal states that the student was required to reach in the simulation environment (e.g., to maneuver a spaceship successfully to a pre-defined location without hitting any walls) [1]. This study compared students who used a version of the simulation with the presence of goal states (games) against students who used an identical environment but without the notion of games. The students using the simulation with games outperformed the non-games simulation group. White concluded that learner engagement and a heightened sense of involvement in the simulation environment enhanced the learner's experience and encouraged their discovery learning processes. Also, the game helped defined explicit goals and a context in which to learn. The importance of setting explicit goals to define the learning process was established by Bransford, et al. [17] in experiments they conducted in the LOGO environment. Students who used the Turtle Geometry environment in LOGO learned to create complex geometric figures. However, post tests conducted showed that the students had learned very little in terms of the underlying geometry that governed the design of the shapes, and in many cases students could not even replicate the steps they had used to create the shape. Bransford, et al. determined that these inabilities could be attributed to explicit goals and anchoring contexts to define the students' activities.

Video games that incorporate simulation environments directed toward educational applications have the ability to provide the anchoring, goal-directed learning, and motivation to support exploration-based learning activities. Unfortunately, the notion of video games has been considered by some to be counterproductive to education [4]. Some educators, parents, and researchers believe that video games take away focus from classroom lessons and homework, stifle creative thinking, and even promote unhealthy individualistic attitudes [5].

Research into the effects of video games on behavior has shown that not all of the criticism is justified [6]. 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.* These are "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" [7].

Games such as SimCity and SimEarth are examples of popular simulation-based games with useful educational content [6]. However, there has been little formal evaluation of the pedagogical effects of these games. It is difficult to determine how much understanding the player has gained and his or her ability to transfer this knowledge outside of the game environment. Moreover, gamers seldom take the time to try to understand the workings of the underlying simulation. Perhaps, being too performance-oriented, the gamer learns just enough about the system to be able to solve the current challenge or task and move on to the next one.

To solve this problem, simulation-based video games for education must provide some amount of the supporting structure to encourage the use and development of regulated, discovery learning and metacognitive skills. Considerations for achieving this are discussed in the next section.

3. Design of simulation-based learning environments

In general, the goal of a simulation-based learning environment is to promote a type of deep learning where students not only learn the current material on hand, but develop a level of understanding that allows them to transfer this knowledge to other problem-solving situations and domains. Deep learning requires the ability to understand, interpret, and reason with the underlying model of the dynamic processes that govern the simulation [2].

The interactions with the learning environment should allow for experimentation with the simulation and exploratory learning in order for this deep learning to occur. Because the learner is quite likely to be a novice in the domain and in exploratory learning, the environment must promote, support, and scaffold this type of learning. Therefore, such a learning environment must incorporate a form of formative self-assessment [11] and introduce and encourage meta-cognitive strategies [13, 14] that support the learning process.

The rest of this section discusses in detail the three primary design goals that must be supported in order to enable students to become effective learners. First the learning environment must support the acquisition of the domain knowledge necessary for understanding the model that drives the simulation [1]. Second, it must support the learner in going through a discovery learning process that helps students to develop scientific inquiry and experimentation skills, and at the same time attempt to correct common misconceptions and mistakes that may arise from prior knowledge [3, 11]. Finally the environment must provide adequate metacognitive support in order help learners' develop the ability to set goals, plan and execute solutions, and monitor their own learning as they go through these processes [12, 13].

3.1 Domain knowledge support

A good simulation tool will play the role of bridging the gap between the "real world" and a more formal model that captures the phenomena and process of interest in the world being studied. There is a tradeoff that must be made here. On one hand, it is important to make the simulation accurate enough to convey correct domain knowledge and represent real world behaviors. On the other hand, making appropriate abstractions to hide unnecessary detail and focus on concepts that successfully bridge the gap between the real world and the formalized model is necessary to help novice learners understand the concepts that are important for the task at hand.

In order to achieve this balance the designers of the simulation must think carefully about what aspects of the real-world model are desirable learning goals. These aspects of the simulation should be modeled in a manner that they are "inspectable" [20], and this will direct the learner to study these entities and their relations, understand them, and reflect on how these relations affect the behavior of the overall system.

It is important to remember that the student learner's use of a simulation is very different from that of an expert's. Experts have a prior working knowledge of the underlying mechanisms of the simulation domain, and they typically use the simulation as a mechanism for making repeated and varied observations on the system under varying conditions of interest, and in deriving the answers for "what if" situations in novel scenarios. By contrast, a novice learner uses the simulation to gain an understanding of the basic concepts and relations that govern the behavior depicted by the underlying model. Therefore, the simulation must be situated in a learning environment that provides mechanisms (such as proper interface controls) for prompting the student to think explicitly about the components of the underlying model, and how they interact to define the overall system behavior.

3.2. Scientific discovery learning support

Learning of complex phenomena does not usually happen in a single step or iteration. Typically, the learning process involves iterative cycles of goal setting, planning, executing, and assessment [3]. For scientific discovery learning this can be broken down into a cycle of "hypothesis generation, design of experiments, interpretation of data, and regulation of learning" [1].

In addition to being a novice in the simulation domain, the learner is also often a novice in the scientific discovery learning process. de Jong and van Joolingen state that learners using simulation environments frequently encounter problems involving all aspects of the scientific discovery learning process. The following are some issues that learners may face during each part of the process:

Hypothesis generation. Learners may not understand what a hypothesis should look like. Even if they do, the learner often avoids hypotheses that they goes against their intuitions or they feel have a high chance of being rejected. This hinders them from constructing complete domain models from the simulation.

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. As a result, students end up designing experiments that are incomplete or lead to incorrect conclusions.

Interpretation of data. Learners often misinterpret data, allowing their pre-conceived notions (hypotheses) to influence the interpretation of data collected from the simulation. Also, learners often find it difficult to interpret graphs that capture the dynamic behavior of the underlying processes. Dynamic behavior of processes may not be correctly understood.

Regulation of discovery learning. Learners may not have the ability to plan their experiments in a systematic manner. Instead they may use random strategies that lead to local decisions that miss out on their gaining an understanding of the larger picture.

Simulation environments must support learners in overcoming these problems that they face in discovery learning. This means providing the learner with some amount of guidance in the exploratory simulation. Although the learner should be free to explore and conduct experiments in the simulation, the learning environment should guide the user towards those experiments which reveal the important aspects of the "inspectable" model. The environment should also provide tools and resources that assist the learner in interpreting the resulting data from the simulation. This could be in the form of information that explains in greater detail some of the phenomena that are observable in the simulation or tools for measuring and extracting information from a graph.

3.3. Metacognitive support

"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 [9].

Although some of the metacognitive aspects of discovery learning (such as planning and goal-setting) are incorporated into the discovery learning cycle as described above (*regulation of discovery 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.

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 for 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 [2].

In order to support the learner's metacognitive needs, the simulation environment must allow (or prompt) the learner to think about the implications of this newly discovered model. This involves thinking about the process by which the learner came to discover this new knowledge of the simulated model as well as the ability to transfer this knowledge to other situations. This could involve reconstructing the model in another representation or apply the newly-learned discovery process to other domains.

Additionally, the simulation environment should include methods for formative assessment [11]. This would allow learners to monitor their learning and enable them to correct their mistakes and misconceptions.

This paper describes an initial study which focuses on the domain-knowledge support of a simulation-based learning environment, gives some amount of discover learning support, and provides the basis for a system that will include metacognitive support.

4. The simulation-based learning environment: a fish tank system

As part of the 6th grade science curriculum in Metro Nashville Public Schools, students study ecosystems and ecological processes. Interdependence and balance are two very important issues in the study of natural ecosystems. We have developed a learning environment that includes a fish tank system simulation as a means for studying a simplified and constrained ecosystem that is still complex enough to bring out the important issues in the study of interdependence and balance.

"For most secondary and post-secondary biology students, the study of biology remains primarily an exercise in memorization. Due to the formidable mathematical prerequisites that quantitative models of biological change have traditionally imposed, students below the advanced undergraduate level are given little or no exposure either to dynamic models or to the process of modeling biological change" [19].

The interacting entities in an ecosystem are typically modeled as differential equations or discrete time state space models. However, this type of model is better suited for expert analysis rather than as a simulation model for a learning environment. In order to create a simulation model with underlying rules that can be inspected through exploration, we have employed a multi-agent approach. This approach accurately reflects the ecological system by modeling each entity (fish, nitrogen compounds, bacteria, and plants) in the fish tank as an agent. Rules are associated with each type of agent and are executed at each time step during the simulation. These agent-specific rules can be relatively simple but still capture the complexity of a dynamic system. When all of the agents interact with one another in an environment, the sum total of their behaviors defines the visible behavior of the real-world system.

Some of the agent actions are randomized (e.g., fish movement), or they occur with a certain probability (e.g., bacteria replication), the simulation is stochastic, therefore, every simulation run may provide a slightly different results quantitatively, even when the simulation parameters are unchanged. This reflects what would happen in a real world environment. Students quickly realize that they may need to run the simulation several times and make multiple measurements or take measurements at several points to compute average behaviors or derive qualitative relations that correctly define expected parameter values and relations between entities. This is an important lesson they learn about the scientific experimentation, hypothesis generation, and verification while working in this environment.

The fish tank simulation was designed to model the nitrogen cycle in an aquarium (the process often referred to as "cycling the tank"). This process involves fish, waste, plants, and two types of bacteria which convert nitrogen compounds from one form to another.

This multi-agent simulation of the river ecosystem was implemented using NetLogo [18]. NetLogo has the advantage of a clean and robust multi-agent programming language and the ability to quickly generate a visual representation of the simulated environment and graphs of the included entities. The fish tank simulation is pictured Figure 1. The fish tank is animated on the right. At the top left are the controls that the student can manipulate. These include turning on and off the presence of different types of bacteria, specifying the presence or lack of plants, and the number of fish with which the simulation starts. Additional controls allow the student to initialize and start the simulation, reset the simulation to the default settings, or add extra fish while the simulation is running. The simulation was exported as a Java applet and embedded in a web-based learning environment with several other components, which we describe below.

The learning environment is centered on "Ranger Joe", a ranger who enjoys maintaining a fish tank in his spare time (see Fig. 2). In addition to the simulation, this learning environment includes a set of short tutorials on the nitrogen cycle and the content of the quiz questions that appear in the "Challenge Zone." The students' goal is to successfully answer the questions presented by Ranger Joe in the Challenge Zone.

Questions in the Challenge Zone help the students assess their understanding of the simulation. These questions are formulated in multiple choice format, and students are free to answer questions at any pace and in any order they desire. If a student answers a question incorrectly, he or she can try again, but the points they can obtain for a correct answer are reduced for each successive attempt (see Fig. 3). This motivates the study to gain a good understanding of the concepts and answer the questions correctly, while making a minimum number of errors.

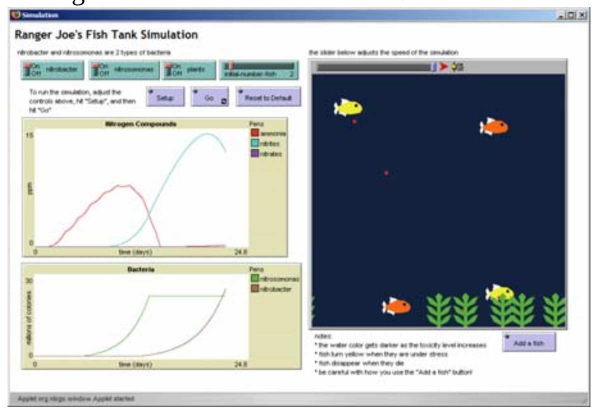

Figure 1. The simulation

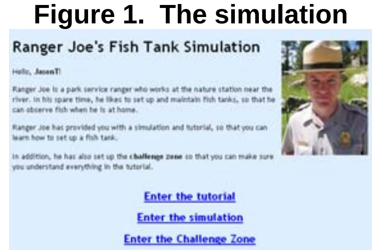

Figure 2. Ranger Joe

To provide the novice learner with additional resources for learning, the Ranger Joe component includes a tutorial on the nitrogen cycle (see Fig. 4).

Figure 3. The Challenge Zone

The tutorial consists of hyperlinked text along with periodic instructions for setting up a particular simulation scenario which illustrates the text. The text material provides background knowledge that aids in understanding the Challenge Zone questions, but it does not directly provide any of the answers to these questions. The answers are derived from interpreting the graphs which are generated by running the simulation.

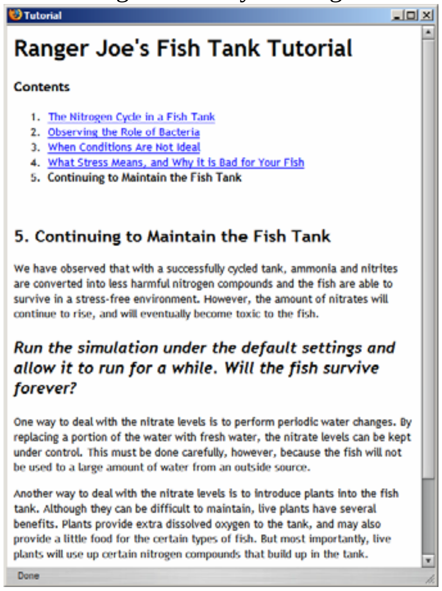

Figure 4. Tutorial (simulation group)

5. Experimental design and results

For an initial study that we conducted in the Spring of 2006, we used 20 participants from a 6th grade science class in the Metro Nashville school district. Our goal was to study the beneficial effects of providing the students with a simulation environment that would allow novice learners to conduct experiments and learn about the fish tank ecosystem. In contrast to the simulation environment, we created a second version of the system, where the students had access to the same Ranger Joe resources, but they did not have the fish tank simulation.

These students were divided into two groups, with a balance of high and low achieving students in each group as designated by the teacher. Both groups were given 50 minutes to work with the system, learn about the fish tank ecosystem, and verify what they had learnt by answering the Challenge Zone quiz questions. The experimental group used the full system as described in the previous section. This group is called the "simulation group".

The control group used the identical "Ranger Joe" system without the simulation. In the Ranger Joe tutorial, the instructions for setting up the simulation were replaced with the graphs that resulted from individual simulation runs with different simulation parameters (for an example of the tutorial content with graph for this group see Fig. 5). This group is called the "non-simulation group".

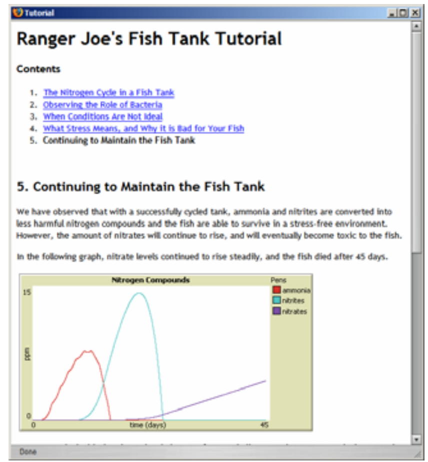

Figure 5. Tutorial (non-simulation group)

Both groups answered the same set of Challenge Zone questions. The Challenge Zone questions were designed to make sure the students went through all of the important concepts we wanted them to learn, and this forced them to read all of the appropriate material in the resources. As discussed earlier, the answers to most quiz questions could be derived by studying the relevant graphs. A second test to determine the differences in learning and understanding between the two groups was administered as a post test a week after the students had used the system. This post test consisted of 3 free response questions and 7 multiple choice questions. Some of these questions were similar to those in the Challenge Zone, but the post test also included more in-depth questions to assess the students' level of understanding of the nitrogen cycle and their ability to apply this knowledge to different problems.

As expected, students from both groups performed similarly on the Challenge Zone questions. The highest possible score was 800 points. Students received 100 points for answering each question correctly on the first attempt. For every subsequent attempt, the score for a correct answer was reduced by 20 points.

The written post tests were administered a week after the students had used the system and consisted of both multiple choice and free response questions. These questions covered general knowledge about the nitrogen cycle and its application to fish tanks. The maximum score on the test was 18 points.

As illustrated in Figure 7, the simulation group scored higher on the post test than the non-simulation group. This difference was statistically significant. (ANOVA: $F_{1,18} = 5.053$, $p = 0.037$)

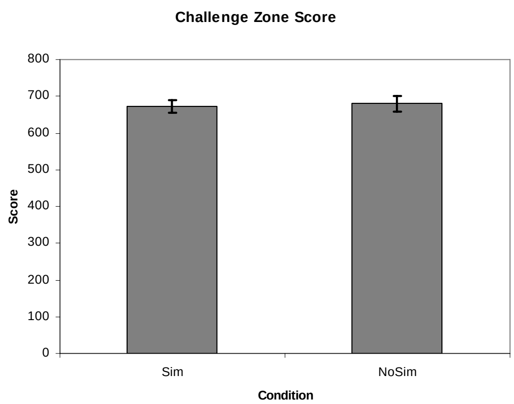

Figure 6. Challenge Zone score (out of 800 possible points)

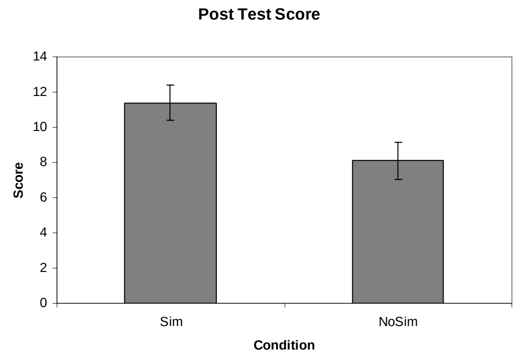

Figure 7. Post Test score (18 max)

In particular, students in the simulation group did significantly better than those in the non-simulation group on questions 1, 5, and 9 (at the alpha = 0.10 level). Question 1 was a free response question asking the students to explain in their own words the nitrogen cycle that occurs in a fish tank. Question 5 asked about the role of a particular type of bacteria. Question 9 dealt with the role of plants in a fish tank, but was framed as a problem-solving question.

6. Discussion

It is evident from these results that both groups were able to learn from their assigned set of resources. In addition to the text resources, all students were provided with graphs that plotted the amounts of each entity in the fish tank over time. The students were able to interpret the graphs and then derive the correct answer to the Challenge Zone questions from the graphs for both the control and experimental conditions. In the first case the graphs were static and included as part of the text resources, in the second case, they were dynamically generated by the students when they ran a simulation experiment. As discussed earlier, these questions provided students with a mechanism to assess their own learning, and enabled them to decide whether they were correctly interpreting the graphs and then understand their implications on the ecosystem behavior as a whole.

However, the higher post test scores for the simulation group implies that they retained the information learned from the system better than the non-simulation group. Overall, the simulation group had a better opportunity to construct their own learning experiences and acquire a deeper understanding of the nitrogen cycle model, resulting in better performance on the open ended questions in the post test.

Therefore, we believe that though both groups learned the same information during the study, the exploratory experiments conducted with the simulation that included hypothesis generation and reflection of the results produced led that group to a deeper understanding that would likely make them more effective in applying this knowledge towards different tasks at a later time.

Additionally, the simulation group appeared to be more motivated and engaged in the task on hand. This was observed in the fact that many of the students in the simulation group wanted to continue using the system even after they had successfully completed the Challenge Zone. The interactive and animated nature of the simulation presented game-like qualities, giving them some sense of immersion into the learning environment. Even though there were no explicit goals embedded in the learning environment other than the Challenge Zone questions, many of the students in the simulation group adopted the goal of seeing how long and how many fish they could keep alive in the tank.

However, the advantages of including the simulation in this learning environment did not rise from the simulation alone. The simulation was situated in the context of a learning environment which provided goal-directed guidance. The text resources gave students just enough information to aid their understanding of the simulation domain without giving away too much information as to make the simulation unnecessary.

7. Future work

This initial study examined the benefits of a simulation-based learning environment which provided domain support and introduced some amount of discovery learning support. The next step is to provide metacognitive support in the learning environment by including a mechanism through which the students can explicitly think about and encode the underlying rules of the simulation. Work has already begun to combine a simulation with the Betty's Brain learning-by-teaching environment. In this system, the student's task is not only to observe and attempt to infer the underlying model of the simulation, but to take this knowledge and teach it to Betty, the "teachable agent." In this process, the student must think about what he or she has just learned from the simulation and frame it in a representation that Betty can understand. By teaching Betty, the student is able to assess Betty's understanding, and in this process their own understanding of the domain. Additionally, Betty exhibits good metacognitive learning strategies as she learns, which enables the student to pick up and employ these strategies.

Another direction that will be pursued is to frame the simulation-based learning environment in the context of a game. One of the most valuable aspects of a video game is the presence of multiple, increasingly difficult goals presented as a sequence of challenges. This game-aspect can be mapped to the fish tank simulation, focusing on different aspects of the simulation in each level. For example, one level might require successfully cycling the tank, which focuses on the nitrogen cycle. Another level might require keeping the fish alive by carefully selecting and controlling the fish's food intake, which focuses on metabolism, production, and consumption. It would be important to maintain a mechanism in the game environment for allowing the student to think explicitly about the underlying simulation model. The difficult part of designing such a game is to create a fun and challenging experience that also requires the student to construct their own model of the simulation rules. This could be accomplished by again using a teachable agent. The teachable agent could be a non-playing character on the student's "team".

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