Virtual Solar System Project:
Learning through a Technology-Rich, Inquiry-Based, Participatory Learning Environment[1]

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ABSTRACT

In this manuscript we describe an introductory astronomy course for undergraduate students in which we moved from the large-lecture format to one in which students were immersed in a technologically-rich, inquiry-based, participatory learning environment. Specifically, undergraduate students used 3-D modeling to construct virtual reality models of the solar system, and in the process, build rich understandings of various astronomical phenomena. For this study, primarily naturalistic inquiry was used to gain a holistic view of this semester-long course. These data are presented as two case studies focusing on: (1) the role of the teacher in this participatory learning environment; (2) the particular dynamics that formed in each group; (3) the modeling process; (4) the resources used, specifically student-developed inscriptions; and (5) the role of technology and whether learning the technology interfered with learning astronomy. Results indicated that VR can be used effectively in regular undergraduate university courses as a tool through which students can develop rich understandings of various astronomical phenomena.

Key Words:
Virtual Reality, Modeling, Constructionism, Astronomy

INTRODUCTION

Throughout the 20th century, undergraduate introductory astronomy courses have been taught in the large lecture format. This format allows universities to present astronomy material to numerous students and allows departments to generate large numbers of credit hours. However, we are currently witnessing increased criticism regarding the effectiveness of the lecture format for university introductory science courses (Baxter, 1991; Carr, 1997; Gilbert, 1982; Solomon, 1983; Tobin, Espinet, Byrd, & Adams, 1988). The Division of Undergraduate Education at the National Science Foundation (1998) recently produced a document, Shaping the Future: New Expectations for Undergraduate Education, that calls for university faculty to make a transition from an emphasis on delivering content through large-class lectures to getting students "involved in some way in scientific inquiry, not just a hands-on experience." In astronomy, inquiry has always been difficult because the phenomena are so far out of reach—students obviously cannot visit the Sun. However, the power of the modern day computer to do desktop virtual reality and computational modeling has created a new opportunity for inquiry approaches to learning (McClellan, 1996; Sabelli, 1994; Stratford, Krajcik, & Soloway, 1998) and for teaching astronomy (Hay, Johnson, Barab, & Barnett, in press).

It is our contention that astronomy education should make a profound transition from an emphasis on delivering content through large-class lectures to a focus on supporting students as they engage in authentic inquiry that involves the construction of scientific models. Lectures, even with slides, overheads, and films help affirm to students that the knowledge is someone else's and, potentially, contributes to the knowledge becoming inert (Whitehead, 1929). The challenge of our design work is how to develop an astronomy course that allows students to directly and concretely engage in scientific inquiry of astronomy concepts that they see of value. Although students cannot visit the Sun, planets, and other objects "out there," they can model these objects and their dynamics on a computer using VR technology. These technologies allow students to enact basic astronomy concepts (e.g. tilt of the earth, period of orbit, etc.) into dynamic, 3-D scale models. Student-created models can then serve as a vehicle for posing inquiry questions (When will an eclipse occur? What would happen if I changed the orbital period?) as they come to understand the solar system.

In the past year, we have been exploring the potential of using 3-D modeling to create a learning environment in which introductory astronomy students build sophisticated models of many astronomical objects, and in so doing learn a great deal about astronomy in an exciting way (Barab, Hay, & Duffy, 1998; Hay et al, in press). We have developed our research agenda as a series of "design experiments" (Brown, 1992), in which we engineer various design modules that are introduced as curricular constraints and that offer new learning opportunities for our students. The interactions related to these modules are then captured using video cameras, interviews, and document analysis so that we can trace the impact of the module and evolve the course curriculum accordingly. The purpose of this article is to present data regarding learning in our hands-on, project-based, introductory astronomy course in which students used 3-D modeling technology to build virtual solar systems.

In this study, we use qualitative methods to understand learning in this context. We begin with a description of our pedagogical commitment and the potential of virtual reality to support students learning in a constructionist framework. A description of the course and research context then follows, with the latter giving rise to a discussion of the five emergent themes that were central to, and framed, this research. Initially, a reflection on the class as a whole is offered. Focusing on the five themes, two case studies are then presented. Reflections on the overall class and the presented case studies provide the backdrop for a broader discussion of the educational implications.

PEDAGOGICAL FRAMEWORK

Currently an increasing number of educators are abandoning predominantly didactic, lecture-based modes of instruction and moving towards more learner-centered models in which students, frequently in collaboration with peers, are engaged in problem-solving and inquiry (Land & Hannafin, 1996; Roth, 1996). This movement is partly in response to the continued criticism regarding the hegemony of the lecture format, especially with respect to university introductory science courses (Baxter, 1991; Carr 1997; Gilbert, 1991; Solomon, 1983; Tobin et al., 1988). Many educators have argued that the lecture format concentrates on memorization of factual information and promotes the development of superficial understandings of the concepts (Roth, 1996; Ruopp, Gal, Drayton, & Pfister, 1993). All too frequently, these didactic models promote the development of knowledge that is non-transferable and that will be forgotten soon after the tests (Barab & Duffy, in press; Cognition and Technology Group at Vanderbilt, 1993; Whitehead, 1929). Still others have stated that large lecture formats do little to correct the many alternative conceptions that students have regarding the foundational concepts of science (Pfundt & Duit, 1991; Wandersee, Mitzes, & Novak, 1994). Further, it has been argued that such approaches have the ancillary effect of stifling creativity and diminishing enthusiasm (Cordova & Lepper, 1996).

In response to the limitations of these teacher-centered or lecture-based learning environments, many educators are moving towards participatory learning environments that support natural complexity of content, avoid over-simplification, engage students in the construction of products requiring practices that embody complex concepts, encourage collaboration, and present instruction within real-world contexts (Barab, Hay, & Duffy, 1998; Barab, 1999; Roth, 1996, 1998). Predicated on a social constructivist philosophy, the role of "teacher" changes from one of telling students correct answers to guiding and facilitating learner activity (Bednar, Cunningham, Duffy, & Perry, 1992; Dewey, 1963; Vygotsky, 1978).

In addition to requiring new roles of the facilitator, these environments are frequently collaborative in nature, requiring students to work with others as they negotiate goals, tasks, practices, and meanings (Blumenfeld, Marx, Soloway, & Krajcik, 1996; Savery & Duffy, 1996). Working collaboratively involves the structuring of the learning environment so that students can work together towards a common goal (Nastasi & Clements, 1991; Sharan, 1994). As such, the role of group dynamics and the need for supporting positive interactions in which all members have legitimate roles to play become central (Johnson & Johnson, 1990, 1994; Slavin, 1995).

Consistent with Papert's (1991) constructionist pedagogical framework, our interest is in learning environments in which learners build understandings through the collaborative construction of an artifact or shareable product. Construc<u>tionism</u> builds on construc<u>tivism</u> in that it distinguishes itself from more traditional instruction, in part, by the degree of active learner engagement as well as the assumption that learners have the ability to create meaning, understanding, and knowledge. Students are not passive receptacles of the knowledge that teachers impart. Nor are they incapable of helping to develop learning goals and discovering and developing meaning from their authentic experiences. Papert (1991) argued that not only can knowledge be built by the learner, but that these processes occur most "felicitously" when learners are engaged in the construction of an artifact or shareable product. Thus, constructionism (for example, learning through the construction of a virtual solar system), allows learners to develop their own reasoned interpretations of their interactions with the world. Perhaps more importantly, constructionist learning environments allow learners to share and collaboratively reflect upon the cognitive artifacts being built.

We refer to these environments as technology-rich, inquiry-based, participatory learning environments for grounding understanding (TRIPLE-GU) (Barab, Hay, Barnett, & Squire, 1998). These environments take advantage of emerging technologies to establish participatory learning environments that immerse students within contexts that challenge, ground, and, ultimately, extend their understandings (see Table 1 for a list of the central features). The emphasis of participatory learning environments is not the teacher’s fixed curricular objectives but rather the learners’ emergent practices in relation to the need at hand. It is a move from a “teacher curriculum” to a “learner curriculum” (Lave & Wenger, 1991), or from an “acquisition” metaphor to a “participatory” metaphor (Sfard, 1998).

[insert Table 1 about here]

Importance of Resources. Within participatory learning environments, it is essential that teachers make available, or support the development of, a rich set of resources that students can use in their projects. These resources can be material, social, or conceptual, and can include facts, instruments, phenomena, and theories that students use while doing their work (Roth & Bowen, 1995). By emphasizing the collaborative nature of these learning environments, students are able to take advantage of the social resources (e.g., experiences of their peers, multiple perspectives on problems; division of labor) as they interact with peers. Newman, Griffin, and Cole (1989) have suggested that students working collaboratively frequently build understandings that go beyond the understandings that either student had in isolation. Further, vocalizing their current conceptions forces students to organize their ideas, challenging the depth of their understandings.

Of particular interest to educators have been resources developed by students themselves. More specifically, Roth and McGinn (1998a, 1998b) have focused on students' building of inscriptions, referring to representations that "exist in material form (e.g., paper, computer screen) and can therefore be shared by several agents, [and can be distinguished] from mental representations, which are not publicly accessible" (Roth & McGinn, 1998a, p. 35). Inscriptions allow the organization, collaboration, and coordination of different group members' contributions. The construction of inscriptions from available resources and group discussions increases students' competence in understanding scientific practices (Roth & McGinn 1998b).

LEVERAGING ADVANCED TECHNOLOGIES

Implementing 3-D Technologies in Learning. Current technological advancements make possible new types of learning experiences, moving from transmission models where technology functions like books, films, or broadcasts to environments in which the technology functions like studios and laboratories in which students immerse themselves within interactive contexts that challenge and extend their understandings (Allen & Otto, 1996). Many such technologies have been discussed in the literature (CTGV, 1993; Edwards, 1995; Jonassen, 1996; Koschmann, 1996; Scardamalia & Bereiter, 1993; Winn, 1995). One exciting technology that has much potential in which to ground learning in rich environments is virtual reality (Dede, Salzman, Loftin, & Sprague, in press; Hay et al., in press; McClellan, 1996; Olson, 1998; Winn, 1995).

Virtual reality has the potential to immerse the learner in various situations (the surface of the Moon or the delicate strand of the DNA molecule), visualize information (the temperatures of a frontal system), see hidden unseen phenomena (forces directed on an object or a tumor in a body), collaborate with people thousands of miles away (in adventure educational games or projects), and bring museum artifacts to the hands of the learners. However, this technology has been, to date, mostly used by the military and the aviation industry to help train soldiers and pilots in complex simulators. In these contexts, soldiers and pilots are put into "real world" situations where they have an opportunity to experience and learn without life-threatening risk. Only recently have educators working with K-12 students begun to explore the educational possibilities of VR learning environments. Researchers examining VR in education have found an encouraging array of positive learning outcomes in a range of projects and domains. A sampling of research findings includes better symbolic retention of human cell organelle information (Gay, 1994), an increase in spatial understanding of architectural spaces (Youngbutt, 1998), understanding of atomic structure (Bynre, 1996), and an increase in low-achievers in drawing mental models of ecology concepts (Osberg et al., 1997), among others.

Using generic VR construction tools, we have been supporting students in building VR solar systems and in the process challenging alternative conceptions (Hay et al., in press). In previous research, it was shown that the process of building an interactive, dynamic virtual model of the solar system created a powerful and unique learning opportunity for students (Barab, Hay, Barnett, & Squire, 1998). In this pilot research, middle-school students participated in a week-long camp in which they built one of three projects: Virtual Indiana Statehouse, Virtual Theater, or the Virtual Solar System. Collapsing across groups, there were significant improvements in students' knowledge from the beginning to the end of the camp. It is important to note that these gains did not come from didactic lectures; rather, the increase in test scores resulted from the completion of practices within the context of the larger project. With respect to the Virtual Solar System project, as students constructed their VR models, previous astronomical misconceptions were challenged, leading to the development of a more realistic sense of the relative interactions of the Sun, the planets, and their moons. In addition to these astronomical understandings, students were also engaged in and learning about the practice of scientific modeling.

Science-Modeling as a Scientific Practice. Current computer advances are transforming science (Sabelli, 1994) and the opportunities for learning science (Stratford, 1997; Stratford, Krajcik; & Soloway, 1998). Sabelli (1994, p. 197) called for "the science education community to consider seriously the educational implications of technology-derived fundamental changes in scientific methodologies." In particular, the methods and processes of inquiry through computational-modeling have dramatically changed science with the ever-increasing availability, power, and “affordability” of graphics computers. What started off in a few specialized sub-fields has blossomed across the landscape of scientific endeavors (Lehrer, Horvath, & Schauble, 1994).

The advent of computational science brings with it new challenges for science educators (Jackson, Stratford, Krajick, & Soloway, 1994; Sabelli, 1994). We need models for engaging students in the process of computational sciences; more specifically, how do we construct learning environments where students build and visualize models to understand scientific phenomena? In a new era where scientific models and visualizations inform public policy, illustrate points in the newspaper, and argue points of public interest, it is imperative that students be familiar with the scientific process of computational modeling (Jackson et al., 1994; Rutherford & Ahlgen, 1990).

THIS STUDY

For this study, primarily naturalistic inquiry was used to gain a holistic vision of the semester long VSS course (Guba & Lincoln, 1983; Scriven, 1983; Stake, 1983). In addition to direct observation and field notes, data were collected with four video cameras, one directed at each of the four groups. Each researcher attended each of the 25 one-and-a-half hour classes, and was expected to continually maintain notes and, when appropriate, posed questions to validate interpretations. In addition to two 20-minute interviews probing student understandings, students and teachers were also questioned during the course to confirm and probe observations made in class, and to gain better understandings about the various emergent issues.

Consistent with the work of Roth (1996), we collected data that: (1) documented practices (e.g., tool use, problem solving, student inquiry) and resources (e.g., concepts implemented, tools); (2) captured the discussions among students and among students and teachers; (3) documented the progress of student projects; (4) traced the same students, artifacts, actions, and procedures over time; and (5) supported and refuted emerging hypotheses about how practices, resources, task constraints, task manifestations, and student understandings evolved over time. The issues were continually refined during fieldwork, group meetings, and increasingly focused data collection and analyses.

Lincoln and Guba (1986) recommended triangulation as one means of increasing the credibility of interpretations derived from naturalistic interpretations. Data were triangulated using multiple data sources, including observations, interviews, document analysis, learner debriefing, and analyses of referential materials. In meetings among the researchers, field notes, learner interviews, and teacher observations were discussed so as to generate assertions used to direct data collection efforts. In particular, these meetings illuminated pertinent issues with respect to the successes and challenges of the course. The issues deemed central to our pedagogical framework and which were most prominent at the end of the study were: (1) the role of the teacher; (2) the particular dynamics that formed in each group; (3) the modeling process; (4) the resources used, specifically student-developed inscriptions; and (5) the role of technology and whether learning the technology interfered with learning astronomy (see Table 2).

[insert Table 2 about here]

In addition to the researcher assigned to each of the student groups, one researcher also carried out two interviews and maintained field notes with respect to the course instructor. In this presentation of the data, we begin with a general reflection on the class as a whole, followed by two case studies that we view as representative of the four groups. Although there were common emergent issues and a common focus, each researcher highlighted and presented their case studies in a unique fashion. Following these case studies, we then reflect on the data to present an overall summary of the course as well as the educational implications.

THE COURSE CONTEXT

In this research, we have been exploring learning/instruction within a collaborative, technology-based, student-centered learning environment—what we have labeled participatory learning environments. The Virtual Solar System (VSS) project is an experimental undergraduate astronomy course taught at a large midwestern university. In the traditional Introduction to Astronomy course, listening to lectures constituted the primary learning activity. In contrast, in the VSS course, listening to lectures was replaced by students building 3-D models of different aspects of the solar system using CosmoWorlds, a VRML editor, on average desktop personal computers. In contrast to immersive VR that places students in the virtual world, the software being used in this course simulates a 3-D environment on a 2-D screen, providing the user what McLellan (1996) referred to as a “window-on-the-world.”

The curriculum was developed collaboratively among an astronomy professor, two educational psychologists, and a graduate student studying astrophysics and instructional systems technology. Two projects were engineered with the expectation that students would model certain aspects on their computers during the semester. These were outlined in detail on the syllabus, which was passed out the first day. The projects were:

1) Project No. 1 was to model the Earth-Moon-Sun system. This included proper sizes, distances between objects, surface features, correct tilts of the bodies, and correct rotation and orbital periods. In addition, students were to provide a cut-away view or a transparent view that showed the interior structure of the Sun, Earth, and Moon.
2) Project No. 2 was to model the entire solar system, including both the terrestrial planets and Jovian planets. Specifically, students were expected to make a model of the Sun, eight planets (Pluto and Ceres as options), six satellites (Moon, Galilean satellites of Jupiter, Titan, and Triton), the Saturn ring system, and with the option of adding comets and asteroids. Again, these bodies must have their proper orbits, sizes, colors, spin, distances, and interior structures.

Student models were expected to address syllabus-delineated questions related to important astronomical phenomena. Each group negotiated plans to answer the questions, identified resources (textbook, WWW, and scientists), designed and built their models, evaluated them, used them to demonstrate answers to the initial questions, and to share them with other groups. Each project had four concluding activities. First, teams created a joint paper describing the features of their model. Second, each student presented and explained their model to students from other groups in an automatic virtual environment (CAVE). The CAVE is a walk-in stereoscopic VR display device that creates a total immersion experience for the learner. Third, students engaged in group presentations in which they demonstrated the functionality of their model to the entire class, using an overhead display in the regular classroom. Fourth, students wrote individual papers that compared and contrasted their project with other projects in the class and with the characteristics of the real solar system. This is a vital step in their learning about the modeling process. It is our position that if students can articulate the difference between their models and the real world they are demonstrating an understanding of the astronomy they are describing at a deep level, as well as an understanding of modeling as a practice (see Confrey & Doerr, 1994; Sabelli, 1994).

It was also necessary to ensure that students be prepared to pass a final examination on the same level as students in other introductory classes. Towards this end, students were given 60 questions from which the final examination would be constructed and which would serve as guidelines for their learning. These questions, taken from review sheets used by the astronomy professor in his lecture-based classes, were given to students on the first day of the class, just as in other classes, so that they could keep the course learning goals in mind. Two of the authors went through those questions and determined that students, potentially, would understand about 45 of the 60 questions simply through building their models.

CosmoWorlds. Students used a virtual reality modeling language (VRML) editor, CosmoWorlds, to build their 3-D models. CosmoWorlds is a multifunctional tool that allows students to create, manipulate, texture, and animate shapes, group and ungroup objects, create various view points from which to view VR worlds, and add or modify light sources, among other features. VRML is the WWW standard for VR and is a language similar to HTML in that it establishes a common standard for making VR easily distributed over the Internet. An example of a VRML 2.0 code is:

```
geometry     Cylinder {height 1 and radius 1}
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This VRML line creates a cylinder 1 meter high and 1 meter in radius that can be viewed on any computer platform that has a VRML plug-in and a WWW browser. Instead of typing in the cylinder command, one simply drags a cylinder from the toolbox into the workspace and sizes it with "handlebars." Whereas adding a color or positioning the object anywhere in the 3-D space would have taken four lines of code similar to the one above, this procedure takes the user of CosmoWorlds only a few clicks and drags (see Figure 1).

[insert Figure 1 about here]

REFLECTION ON THE CLASS AS A WHOLE

During the first couple of weeks, just learning the software occupied much of the students' time. The decision was made by the instructors to allow the students to explore the software and learn it as they progressed through the projects rather than directly teaching them the software. This decision seemed to create anxiety among the students and, due to the steep learning curve of the software, probably stunted their exploration of some of the richer astronomy concepts.

The first project was intended to ground the students in both using the VR software and in fundamental astronomical concepts. These goals were only partly reached, due to the instructor’s lack of understanding of the software, lack of experience in teaching a constructionist-based class, and the conceptual and technical difficulties that the students were faced with in the first project. Further, the use of the tools was not "transparent" (Lave & Wenger, 1991), thus creating a steep learning curve that potentially interfered and even competed with learning the astronomy content. Yet, despite these problems, the students formulated insightful questions concerning both astronomy and the effects of software limitations on their projects.

A particularly challenging problem for the students was the understanding of phases and eclipses. Several discussions were held with each group regarding what was needed for eclipses to occur. During one exchange, there was much discussion on important theories, such as the Earth's tilt, the Moon's orbital plane tilt, the Moon's elliptical motion, and the role that the relative position of the Earth, Sun, and Moon plays in the occurrences of eclipses. Further, CosmoWorlds' algorithm for handling the rotation of objects created a great deal of thought concerning what needed to be done if their model was to accurately represent the rotation of the Moon. This discussion was prompted by technical concerns, but required students to grapple with astronomy concepts (see the design module discussion in the next section below).

At the end of the first project, the students were more confident concerning their understanding of CosmoWorlds and their astronomy knowledge as demonstrated by their first papers and student interviews. However, the increase in confidence was not universal among team members and, at least for the groups of three, it was greater for the "team leaders." That is, in each team there was one individual who emerged as leader, appearing to be central to the modeling process. These individuals submitted the best papers and generally had more thought behind their arguments and comments than students who played a secondary role in the development of the projects. In addition to differences in overall confidence, there were also individual differences with respect to their modeling responsibilities (e.g., modeling planetary orbits vs. modeling planet cross-sections). Each student had the greatest degree of expertise with the content that they were responsible for modeling.

The second project began differently because the students learned from their mistakes and successes (as well as those of other teams) of the first project. Each team took some time before the second project to plan and develop strategies for building the second project. The teams in general did more reading and researching before they began their modeling. From a science and learning perspective, this was refreshing because we were not only trying to foster students' understanding of the astronomy, but also their problem-solving ability which starts with the step of defining the problem at hand and developing a strategy to solve the problem. In addition, each group developed inscriptions, a practice central to doing science (Roth, 1998). The most common inscriptions developed were tables in which they converted the distances and sizes of planets recorded in the back of their textbooks to numbers that they would use in CosmoWorlds.

As the second project progressed, the students become more and more disenfranchised with CosmoWorlds' functionality and limitations. The main problem was CosmoWorlds' limitation of 3000 frames (300 seconds) for any animation. Students continually struggled with developing a scale that fit within the time limitation of the software and still demonstrated the important astronomical concepts that they wished to model. Further, the students had to decide whether to create their models to scale, which was hard to visualize and work with in CosmoWorlds but better represented the real solar system than models not to scale. In determining the size and distance of planets, students used mathematical algorithms to instantiate numbers derived from their textbook and the Internet into inscriptions of functional value for building their models. We believe that working with issues of scale to build models has much potential for understanding astronomy. Further, it allows students to see the value of mathematics, as a tool for addressing their needs not those defined in a textbook. As one student said during the pilot work, "Wow, finally a use for math!"

Another change in the second project was the amount of cross-project diffusion of knowledge/practice. For example, students began to share their inscriptions and to ask other groups how they accomplished certain phenomena. On multiple occasions, all four teams would gather around one team's computers so they could demonstrate how they tackled a particular modeling problem. One example of such an exchange was with respect to modeling the proper tilts of an eclipse. What was exciting in this case was how one group learned how to link objects and rotate the linked Earth-Moon object, and another group then learned the subtleties of using local/relative center and view points from which to orbit and observe these rotations to experience an eclipse. They then pooled their experience to produce their dynamic models. During this process, one of the students commented on the complexity of the interacting bodies in our solar system: "It is amazing that they all don't collide."

On multiple occasions, the instructor was asked questions he was incapable of answering to the students' satisfaction (mostly concerning the software), and on several of these occasions, the students would investigate the problem further and develop their own solutions. At different points during each project, the students would struggle with a particular astronomical concept or superficially discuss a topic. At these times the instructors would interject with short, "just-in-time" lectures (under 10 minutes) to respond to student concerns. These lectures did not involve the instructor telling the students what to do, but rather helped frame the context and clarify the problem. These lectures were usually proceeded by (and littered with) Socratic questions, facilitating students' formulating a better explanation or solution to the problem at hand.

An exciting learning potential of models occurs when students pose questions to their models (Confrey & Doerr, 1994; White & Frederikson, 1998). In this manner, students can develop hypotheses about the phenomena of interest and verify these conjectures using their models. In our VSS course we saw this potential being actualized both through student-posed questions and through Gedanken (thought) experiments posed by the course instructors. An example of a Gedanken experiment occurred early in the semester. In this challenge, students had to use their understanding of the Moon's synchronous rotation with respect to the Earth (i.e., that we always see the same side of the Moon) to answer the following question: "If you walked outside at night and could see a neon flag on the Moon, how many other clear evenings of the month would you be able to see it?" In general, students were unsure about the response, so the instructor developed a model in which he placed a lit object on one side of the Moon and then rotated the Moon about the Earth. In this case, we used the CAVE so that students could actually experience the Moon (and the neon flag) orbit around them with the flag always being viewable. However, one individual still was not convinced that we would always see the same side of the Moon, so he and his partner went back to the classroom, put an object on their Moon, and put it into orbit. It appeared that the student did not believe the instructor's model and had to develop the representation for himself. At this point, the student stated with confidence the correct response to the experiment: "every night."

Throughout the class, there were also stand-and-deliver sessions, intended to probe students' understandings of various astronomy concepts. Student papers revealed deep understandings of astronomical concepts such as line of nodes, rotation of the Moon, and orbital motions. In addition, the papers revealed a considerable appreciation of the scientific process, in that students were developing, revising, and constructing plans and hypotheses to improve their models so as to better understand the concepts at hand. Surprisingly, students showed varying improvement in their geometric knowledge, and in understanding of scale. We have already begun the process of fine-tuning and adapting the class projects assigned and we are confident that these changes will help the next set of students in successfully mastering these concepts. One occasion in which students demonstrated their understandings of scale occurred when they had to share their models with members of the other teams. During these occasions, students questioned other groups, "How did you determine scale?" or "Why did you choose those numbers?" At one point, one of the groups demonstrated their Earth-Moon-Sun system and a member from another team immediately saw what he believed to be a limitation, saying, "Your numbers can't be good because the Sun would be too far away … and you show it." The presenting group actually handed their table of numbers to the individual, and eventually she conceded, "the numbers look good."

The results of student performance on typical multiple-choice-question final exams and follow-up interview questions were also examined (Keating, Barnett, & Barab, 1999). To this end, students were given the same final exam as a previous lecture-based class. The VSS students performed better on questions that required conceptual understanding rather than just memorization of facts in comparison to students from the traditional class. For example, students developed rich understandings of the relationships between colors and temperature, of differences between sidereal and synodic periods, and of the relationship between the orbital alignments of the Sun, Earth, and Moon, and whether or not eclipses occur. The largest difference occurred on questions that challenged the students to change their frame of reference. For example, the students were able to predict what phases the Earth would have when viewed from the Moon or even another planet. This ability cannot be understated because it is fundamental to understanding much of science—particularly at a more advanced level.

CASE STUDIES

Butch and the Sundance

Introduction. Butch was a member of a fraternity and Sundance was a student from the local high school. Butch was typically the leader of the group and the one who was most excited about the innovation of the course. Butch often persevered through the project challenges that would flare up from time to time. Sundance was eager to learn, but was much quicker to get frustrated. They both attended class regularly and engaged the projects thoughtfully. Butch had some computer background through his business degree program. Sundance was comfortable with using the technology, but did not have any special computer training.

Opening Challenges. One of Butch and Sundance's first challenge was the definition of the center of the solar system. After developing skills at creating and sizing spheres in CosmoWorlds, they began moving the planets with the direct manipulation interface. Sundance created the Sun and put it into the center of the screen, which he interpreted as the center of the solar system. However, when he used the CosmoWorlds "thumb wheel" tool, the Sun wobbled like a poorly-centered piece of clay on a potter's wheel. He reasoned that it was not in the center, so he moved the thumb wheel to the point where it was wobbling the most and dragged the Sun toward the center. Sundance spent a lot of time on this and came close to centering it. He asked Butch periodic questions and at one point Butch used a ruler to help find the center. It was later revealed that this practice emerged as a result of a particular artifact of the software. CosmoWorlds allows the user to "grab" the entire virtual space and spin it like a globe. This is one of the first features Butch and Sundance came to understand and they used it as their first "model" of how to create planetary orbits—it allowed them to create a sphere that was not at the center of the "virtual space" and to make it spin around its center. However, this model had a number of operational flaws. The first flaw was that the orbit speed was determined by the speed which Sundance or Butch would click, drag, and release the mouse button. That is to say, it was not based on data about a particular planet's orbit. Another flaw in their first model was that unlike a globe, the virtual space could be spun around a single point instead of an axis. Thus, the direction of the click, drag, and release of the mouse would determine whether the virtual space would spin about the X-, Y-, or Z-axis or somewhere in between. Finally, the model was flawed because when more planets were added, the period of their orbits would be exactly the same, which is in fact not the case.

Although these flaws are profound, at this early point they did not concern Sundance because once he accepted this model, his primary concern was to put the Sun in the center of the world. Sundance defined the center, in his mind, as the point where you could place an object and it would not move when he used the thumb wheel to rotate the virtual space about the X-, Y-, or Z-axis (the center of the "potter's wheel" in 3-D). This proved to be difficult because the center of the "potter's wheel," and of 3-D space is hard to find. Also, the Sun was the center of the current viewpoint of the world, not the absolute center of the virtual space, adding a second element of complexity. This second issue created much frustration because when Sundance got close and changed the scene, he basically had to start over because the viewpoint and its center changed. Conceptually, Butch broke through the shortcomings of this approach when he challenged Sundance to create the Moon's orbit. Adding a second object became problematic because his process of creating orbits relied on the creation of a new center in the virtual space. In other words, every time he added an orbit he had to change the center of the universe, which affected the accuracy of previous orbits. The Moon orbits the Earth, not the Sun. The challenge forced Sundance to abandon his first model of a planet's orbit.

<u>Project Two</u>. Project Two was marked by several events. First, was an intense planning session where Butch and Sundance sat down and created an elaborate plan where the planets, moons, and, most importantly, viewpoints were going to be placed. The experience of Project One gave them a clear understanding of what they wanted to create and the necessary approach to take. The second event was that Butch and Sundance's skill level was at a point that the technology became "ready at hand" and even "transparent" (Lave & Wenger, 1991). That is to say, it no longer was the primary focus, but rather was a tool to see and model the rest of the solar system. They successfully moved from frustrated novices to rather accomplished modelers.

<u>Technical Struggles</u>. One of the more difficult tasks Butch and Sundance engaged in had very little to do with astronomy. This activity was the labeling of cross-section layers and arrows connecting labels to the layers. This seemingly easy task took considerable effort because they were working in three dimensions. When they put a label and a connecting arrow on an object, it would frequently not be on the same plane as the planet. So Butch and Sundance would work and create all the labels, but when they moved to another perspective, the labels and arrows would be floating off into space, not pointing at anything. This could have been avoided through the software, if it were to default to putting labels on one of the origin planes (X, Y, or Z planes) or the plane of the

object. However, Butch and Sundance eventually began to use all three dimensions, but time was taken up in trying to position these labels.

Tool-Related Practice. The practice of setting viewpoints created an interesting dilemma for Butch and Sundance. Viewpoints are the points that direct the view of the person looking at their model. CosmoWorlds uses the metaphor of a camera to define these viewpoints. You place a camera at a specific spot and name it, then when people go into your world, they select the viewpoint by name and are quickly transported to that position looking in the direction that was pre-specified. Conceptually, viewpoints are very important for students' understanding of astronomy. Like most scientific observation, finding the correct location is the key to understanding, and in the huge vastness of space, you need to look at something in a particular way to understand specific relationships. For example, a quarter-moon does not make sense from just any position. The observer has to be in the right place, and looking in the right direction at the right time to see a quarter-moon. Viewpoints create the opportunity for students to construct observations of the Earth-Moon-Sun system in the quarter-moon position as we see it from Earth, from the Sun, from the Moon, and from outer space. In constructing these viewpoints and viewing the Earth, Moon, and Sun from these positions, students can build understandings. In other words, they can used viewpoints to ask questions of the model.

Butch and Sundance found the use of viewpoints to be difficult. They quickly mastered the setting of global viewpoints and moving between them in CosmoWorlds. Global viewpoints are viewpoints that are fixed at an absolute position relative to the world. The challenge came when they wanted the cameras to move with the objects. These types of viewpoints are called local viewpoints. Local viewpoints are critical to see most of the interesting relationships of the Earth-Moon-Sun system because these interesting relationships involve the movement of the Earth and Moon around the Sun. If you put a viewpoint looking at the Earth and Moon at the starting position, as soon as you enter the world, the Earth and Moon will immediately disappear and will only return to your view once a "virtual year" has passed.

Butch and Sundance worked collaboratively, further refining their abilities by learning how to "make visible" the viewpoint icons (cameras) in their world. While it is not important to see the “camera” in setting global viewpoints, you can just move yourself into position and set the global viewpoint to your current position, when you create and animate local viewpoints seeing if and where the camera is moving is critical. Another snag is that local viewpoints are grouped with an object, but, if the object is animated, it will not move in the same way the group moves. This caused Butch and Sundance much frustration, to the point where they almost gave up. At one point, Butch said "Lets just set the dynamics and screw the viewpoints. I hate viewpoints, I hate this, I HATE YOU!" to the computer. There was some significant intervention by the instructor to help them work through the issues, to attempt several different fixes, and finally to come to a resolution. The solution was to simply treat the camera as any other object and rotate it at the same rate as the objects they wanted the viewpoint to illuminate.

Conclusion. Sundance and Butch had a conversation somewhere in the middle of the course that was recorded on videotape. During a moment of frustration, Sundance asked Butch why they are taking the course using virtual reality. Butch replied that he was excited to be in this experimental course and that he would be putting this course on his resume because he thought that it would help him get a job in business. By the end of the course, Sundance came to understand the value of what they were doing, stating that this was one of the most challenging and rewarding courses he had taken.

The Three Ninja Turtles

Group Description. This team consisted of three male members: Donatello, Leonardo, and Rafael. They ranged in computer experience, astronomy background, and educational level. Donatello was a graduate student with fair computer knowledge, but only basic astronomy knowledge. Leonardo, an upper classman, entered the course with good computer experience and some astronomy knowledge, having already completed one college-level astronomy course. Rafael, an underclassman, entered the course as a relatively inexperienced computer user with no background in astronomy.

As the course progressed, each student began to take on specific roles within the group. After only a few class sessions, Donatello, the graduate student, emerged as the group leader. He initiated most of the planning activities, and exerted a strong influence on the direction of the project. A key point in Donatello's development as a leader occurred early in the second project, when Donatello conceived, designed, and developed a master planning document for the group. This document contained all of the data that the group needed to develop the second model, including the sizes, distances, orbital periods, and rotational periods of the planets and major moons. Thus, Donatello quickly became the gatekeeper of astronomy information for the group, although Leonardo also served as an astronomy resource throughout the semester. Donatello also engaged in the most discussions with instructors, both in and out of class, adding to both his astronomy knowledge and knowledge of CosmoWorlds. As a result, Donatello became a CosmoWorlds resource for the group, helping other group members learn to position celestial bodies, create animations, and create viewpoints.

In contrast to Donatello's strong presence in the group, Rafael was much less involved in group processes. Rafael attended fewer classes, and during the second project he missed four of six classes. In both projects, Rafael focused on creating the cross-sectional views of the planets, which limited him to astronomy tasks that involved more direct input of factual data as opposed to the creation of orbits, rotations, and complex astronomical phenomena. As a result, Rafael was called upon only as a resource for using the CosmoWorlds tool to create cross-sections and very rarely for astronomy-related content. In the interviews, Rafael commented that he knew the interiors of the planets much better than other astronomy concepts, and would essentially have to learn the other astronomy concepts on his own outside of class time.

The final group member, Leonardo, was fairly involved in team-building activities and the building of the virtual worlds. In Project One, Leonardo worked with Donatello on many of the model planning and building tasks, although he tended to work more independently in Project Two, serving as a less central member of the group. Leonardo engaged in the full range of tool-related practices and delved into a wide range of astronomy related concepts. For example, Leonardo created the complex Jupiter and Saturn moon systems, affording him opportunities to wrestle with issues of relative scale, orbits, retrograde rotation, and cross-sectional views. In building these models, he engaged in all of the critical tool-related practices.

Project One. On the first project, the team collaborated on many of the model-building and planning tasks. Leonardo and Donatello were especially productive together, creating most of the group's orbits, scales, and animations as a team, which afforded them opportunities to discuss and reflect on concepts as a dyad. For example, when attempting to model the Earth's orbit around the Sun, Donatello and Leonardo experienced difficulty maintaining the correct tilt of the Earth. After much deliberation, they decided that this flaw in their model was important because it prevented their model from depicting the seasons in an accurate manner. Before arriving at a solution, they consulted texts, charts and tables, developed makeshift physical models with mousepads, and called upon the instructors to answer questions. In doing so, Donatello and Leonardo became deeply engaged using astronomy resources to think about astronomy-related content. Similar discussions ensued as Donatello and Leonardo attempted to model the Moon phases and incorporate the Moon's 5- degree tilt from the plane of the ecliptic into their model. Rafael was very rarely a part of these discussions, as his work concentrated on creating the interiors of the Earth, Sun, and Moon.

In interviews, the team agreed that much, perhaps even most of their energy in the first project was dedicated to learning CosmoWorlds, engaging in relatively little astronomy-related content. Learning to create viewpoints, for example, was an especially difficult skill for group members to learn, with several hours of class time devoted solely to learning this process. On several occasions, Donatello and Leonardo had to redo entire animations because they did steps out of order in setting viewpoints. Other times, Donatello and Leonardo both felt that they understood the astronomy concept that they were attempting to model, but CosmoWorlds limited their ability to efficiently build models. For example, Donatello and Leonardo spent considerable time attempting to model the Moon's 5-degree tilt about the plane of the ecliptic, redoing their entire model several times in the process. After hours of experimentation, they developed a solution, giving the Earth an 18-degree tilt, then adding on the Moon's orbit and finally tilting the whole system another 5-degrees to get the Earth's proper 23-degree tilt as well as the Moon's 5-degree tilt around the Earth in the same model (see Figure 2 for a screen shot of the virtual Earth with a 23-degree tilt).

[Insert Figure 2 about here]

While the limitations of CosmoWorlds impeded their progress and caused some frustration, it also forced the team to grapple with astronomical relationships in very meaningful ways. In another example, the group had difficulty with CosmoWorlds when modeling the orbits of the Earth, Sun, and Moon. Donatello and Leonardo spent most of a class period attempting to track the Earth's orbit around the Moon, but the relatively small size of the Earth and the vast distance between it and the Sun made it difficult to find. At one point, the group was unable to determine if they had modeled this phenomenon correctly, because they could not see the Earth in their model. Finally, they reconstructed their model with the proper viewpoints in order to prevent losing celestial bodies, and learned about key astronomical concepts, such as the "empty" nature of space, the dramatic size differences between the Sun, Earth, and Moon, and the vast distances between celestial bodies.

Project Two. Fresh from their experiences in Project One, the team took a very different approach to Project Two, spending multiple class periods defining the tasks and approach for completing this project. Drawing from their difficulties in incorporating all of the relevant aspects of the Earth, Sun, and Moon system into one model, Donatello proposed a four-level approach to modeling the solar system. The first level attempted to model the relative size, scale, and distance of the planets without any animations. Level two would also include the animations of planets around the Sun, the accurate relative sizes of the planets and the accurate scaling of distances, but would dramatically shrink the distances between planets so that multiple planets could be viewed on the screen at once. Level three would contain the moon system of each planet, and level four would contain the interiors of each planet. Each level would be connected by links, making the model appear to the end user as one seamless model. The team was hopeful that this multi-leveled approach would allow them to view important astronomical concepts and relationships in their models without making factual compromises.

The amount of energy this team invested in planning Project Two also manifested itself in the team's planning document of inscriptions. Immediately following the completion of Project One, Donatello realized that it would be valuable to have all of the key information for the project in one central location that the team could use to build their model. He created a document containing information about the planets, with all data converted into values that could be easily plugged into CosmoWorlds. This conversion process involved much planning and calculation. For example, in depicting the planets' orbits, Donatello needed to develop the optimal mathematical factor by which he could collapse the distances of the planets from the Sun so that the inner planets were viewable, while still retaining enough distance between the planets so that Mercury was not swallowed by the Sun. The understandings embodied within the sheet were developed by Donatello, with Rafael and Leonardo contributing little to this process. As a result, Donatello soon became the gatekeeper of information and emerged once again as the leader of the project.

With the planning for Project Two completed (mostly by Donatello), the group functioned much more independently in the actual model building process than they had in Project One. Donatello handled the most complex activities, creating the relative size and scales for the planets, the planets' orbits, developing interesting viewpoints that would depict astronomy relationships, and building complex extra features into the model (levels one and two of the model). Donatello spent several days thinking of and creating viewpoints that would yield interesting astronomy insights, which led him to several engaging discussions with the instructor. Donatello further elaborated the model by creating the Neptune, Pluto and Charon system, which includes the elliptical orbit of Pluto and the twin system of Pluto/Charon. The animation attempted to model some of Kepler's laws by showing how Pluto's velocity increases as it approaches the Sun, and slows it as it moves toward the furthest points of its orbit. Although Donatello gained a deep understanding of those aspects he modeled, he later commented that he missed the opportunities to learn about planetary composition that came with building the planets' cross-sections. In interviews, he lamented that in preparing for the final exam he would have to learn those concepts and facts on his own.

Leonardo also engaged in fairly complex modeling activities, building the moon systems and cross-sections for the outer planets. He developed the moon systems for Jupiter and Saturn, as well as Uranus' unique rotation. Leonardo elicited help from Donatello with some of the more complex modeling procedures, such as the Saturn moon system and Uranus' rotation. In contrast, Leonardo only asked for help from Rafael in purely tool-related practices; he often asked for help in operating the coloring and labeling functions of CosmoWorlds. In the elaboration phases of the project, Leonardo gravitated toward activities that demanded mastery of CosmoWorlds, but not necessarily rich astronomy understandings. Leonardo added an asteroid belt for the project, seeming to enjoy himself as he created thousands of tiny objects and began animating them about the solar system. Inspired by the movie Deep Impact, Leonardo even began an animation that featured a rocket being blasted toward an asteroid that was hurtling toward the Earth. This activity afforded the instructor an excellent opportunity to push Leonardo toward making a realistic model of this event. In doing so, Leonardo quickly understood why the high velocity and relatively small size of asteroids make intercepting an asteroid that is headed toward the Earth nearly impossible.

Rafael engaged in the least complex modeling activities of Project Two, specializing in creating the cross-sections of moons and the inner planets. Modeling the inner planets allowed

Rafael opportunities to gain expertise in tool-related practices such as labeling and coloring, but very little experience in setting viewpoints, creating animations, and understanding orbits.

Conclusions. In closing interviews, the participants were pleased with their performance as a group, and with what they learned in the course. All team members expressed satisfaction with the dynamics of the group, feeling that they got out of the group what they put into it. The team seemed to appreciate and value Donatello's role as a leader, and no reservations about team member roles were expressed. All team members expressed some concern that they missed opportunities to engage in some areas of astronomy content by specializing in others. Likewise, each team member agreed that too much of their focus was placed on learning the tool during this course. Optimally, the team would like to see more tutorials, job aids, and direct instruction on using CosmoWorlds. As Donatello commented, "If the point of the course is to get us to learn to use computers, then fine, but if it's astronomy, just show me how to use it, and let me concentrate on the astronomy."

The group members also agreed that the direct instruction, such as lectures, on astronomy-related content, were quite valuable. They agreed unanimously that the professor's just-in-time lectures were one of the most enjoyable aspects of the course, and they expressed a need for more lectures on other topics, especially over material that was not covered through building their models. In comparing their experiences in this course to other more traditional courses, group members felt that they "probably didn't learn as much" but did understand what they learned much more in depth. For example, Rafael felt that he never really understood tilts until he was forced to model them. In summary, Leonardo commented that "Other students might learn more, but a year later, I will remember more of it. In other classes, I didn't remember much."

DISCUSSION

The VSS course was designed to support students as they constructed concrete artifacts and, in the process, rich understandings of astronomical phenomena. Specifically, our data collection focused on the following issues: (1) the role of the teacher in this participatory environment; (2) the particular dynamics that formed in each group; (3) the modeling process; (4) the resources used, specifically student-developed inscriptions; and (5) the role of technology, and whether learning the technology interfered with learning astronomy.

Role of Teacher. In constructivist learning environments, the teacher's role is reconfigured, from didactic caretaker and keeper of knowledge to a facilitator of the knowledge construction process, directing students down profitable paths, modeling an engaged mind, problem-solving with students, and providing a rich context with needed resources (Savery & Duffy, 1996). Most interactions between the instructors and the students were Socratic in nature and were centered on the students' model or the modeling process. When the instructor observed students struggling with a difficult astronomical concept he would ask the students the question: "What does your model say?" If the students could not answer this question by manipulating their model, the instructor would ask the students what needed to be added to their model to answer the question. This dialogue would lead the students to modify their models until they could answer the questions (including more formal Gedanken experiments) by studying their model. Most importantly, these questions allowed students (and instructors) to determine gaps, and to aid students in improving their models (and their understandings) without students losing ownership over their models and the learning process.

In general, the instructors maintained this role of facilitator. However, the instructors did present several "mini" or what the CTGV (1993) called "just-in-time" lectures throughout the course. These "mini-lectures" were delivered when students appeared confused or frustrated, or needed to understand a particular astronomy concept to continue their work. Although these lectures occurred most often in response to individual group concerns, occasionally when the instructors would observe similar difficulties across multiple groups they would present a just-in-time lecture to the entire class. Another teaching technique that the instructor used was to have "stand-and-deliver" sessions in which one student would attempt to describe challenging concepts to the rest of the class. If the student failed to demonstrate a satisfactory understanding, another "stand-and-deliver" session would be held the next class session, allowing students time to research the issue and formulate a response to the instructor's questions.

<u>Group Dynamics</u>. There appeared to be very different group dynamics both between groups and among groups over time. The most obvious difference was between the groups composed of two students and groups of three students. Groups of two students tended to work collaboratively over the entire semester. In contrast, in the groups of three, one member of each team appeared to be central to the modeling process. The leaders of each team submitted the best papers and generally had more thought behind their arguments and comments than students who played a secondary role in the development of the projects. Further, students had the greatest degree of expertise with the content that they were responsible for modeling. While increasing depth of understanding is important, steps need to be made to integrate student responsibilities so they learn about "all" aspects of the group's model. We are currently addressing this limitation by placing greater emphasis on the follow-up activity in which one student from each group is held responsible for explaining her group's model to members from the other groups.

The most notable similarity among groups was in terms of the groups' transition from reactive participation to active participation. Initially, group members simply did what was next, spending little time planning out tasks and individual responsibilities. As a result, first projects were ill-conceived and lacked the sophistication of the second project. In contrast, in Project Two, teams spent much time planning, gathering resources, and dividing up responsibilities, resulting in a higher quality project.

Modeling Process. The practice of modeling occurred in two stages, an enactment stage and a visualization stage. The first stage in the students' practice of modeling was the enactment stage. For example, students begin with questions like "When does an eclipse occur?" In a traditional course, the lecture would contain a definition and an assortment of two-dimensional drawings. The focus would probably be on the difference between lunar and solar eclipses. In the VSS course, there was no lecture. Students started by collecting resources and planning the model they would build to answer the question. Following the collection of resources and planning, they began the construction of their virtual models. Students enacted the facts and concepts about the Earth, Moon, and Sun they collected. Facts such as the 23-degree tilt of the Earth, the 24-hour day, or the 13-degree motion of the Moon against the background stars were enacted when students constructed their VR models.

The second stage is the visualization stage. Once the virtual model was built, students used the model to answer their initial question(s). However, this requires significant planning and thought by the students. Students engaged in systematic observation of their models. They created "viewpoints" from which to "see" their models at appropriate times. In science, knowing when and where to look is sometimes the most important aspect of an investigation. Students attached viewpoints to objects (say, the Moon looking back at the Earth to first detect an eclipse) to create relative perspectives. They then were able to move to other "global" viewpoints to see the relative positions of the Earth, Moon, and Sun.

Finally, students used visualization techniques to view important relationships. To answer questions about an eclipse, students in the VSS course used the visualization technique of constructing transparent disks to visualize the Moon's orbital plane and the plane of the ecliptic. The intersections of these two planes form the "line of nodes." When the Earth, Moon, and Sun are all on the line of nodes, an eclipse occurs. This became readily apparent as students visualized these planes. The concept of "line of nodes" is often left out of introductory astronomy courses because the dynamic, three-dimensional nature of the concept is so difficult for students to understand at a meaningful level. Another difficult concept for students to grasp is the vast variety of scales of size in astronomy (e.g., the fact that the distance of the Moon from the Earth is 60 Earth radii—in other words, the Moon is far away from the Earth; or that the distance of the Earth from the Sun is another 400 times larger than the distance of the Moon from the Earth). This is difficult to communicate through a textbook or even a carefully planned lecture using pictures and slides; however, as students enacted these distance into their virtual models they were able to immediately experience these distances by zooming in and out of the appropriate scales. The power of the modeling process in which that students constructed “their” models was evident in one student’s post interview:

> I definitely saw this as much better than a lecture-based course. Many times during a lecture-based course I may get lost or might not be that attentive. This is impossible with this project since it is so independent and I have to do it myself. The self-motivation and independence makes it vastly more interesting than the mandatory listening to a professor speak his mind…I have been in both A105 and A115 astronomy classes. And by far, I have retained more information in this A100 intro class than both two classes combined.

Resources and Inscriptions. The primary resources used by students were their textbooks, the on-line syllabus, the World Wide Web, the CosmoWorlds tutorial, each other, and the instructor. With respect to the textbooks, the instructor stated, "In all my years teaching this course, I have never seen books that were so marked up and dog-eared." Initially, students relied heavily on their textbooks, on-line supports (e.g., tutorials, the syllabus) and the instructor. However, during the course they became more reliant on the other members of their own group and even went to other groups as a resource. Some of the most exciting resources were the inscriptions developed by the students themselves.

In our VSS course, students constructed inscriptions (tables, formulas, charts) after prolonged discussion concerning astronomical data found in their textbook, the WWW, or told to them by the instructors. Student-developed inscriptions were not widely used until the second project in which students were confronted with the modeling of significant astronomical data and concepts. For example, before Donatello's group began the construction of their Earth-Moon-Sun model, the group spent two class periods researching their textbook and the WWW for the necessary astronomical data needed to create a realistic model. They tabulated their findings in a single inscription (table of numbers representing astronomical sizes and distances, and list of steps necessary to the modeling process). This inscription served the group as a memory device (keeping track of what parts of the model were incomplete), planner (timeline), task management check (which group member was responsible for which portion of the model), and final check of their model (similarity of their model to the real solar system). During the construction of their model, group members continually referred back to the inscription to verify their model's properties, which facilitated each group member's ownership and understanding of the overall model. These inscriptions stimulated discussion, and were instantiated into the model construction process once students recognized the value of sharing their ideas and planning their strategy for constructing their models.

Technology vs. Astronomy. Initially, students spent a great deal of time learning the software tool and, at times, its lack of usability and intuitiveness created frustration. This was evident in the student's above statement regarding whether the goal of the course is to learn astronomy or the technology. However, on other occasions, the technology prompted students to engage in debates with their peers and instructors concerning astronomical phenomena and concepts.

For example, a particularly challenging issue was modeling the necessary conditions for the occurrence of eclipses. The students could not model an eclipse with complete accuracy and maintain relative scale between the Earth, Sun and Moon due to limitations in the software. Eclipses are possible because the Moon and the Sun appear to be about the same angular size in the sky when viewed from the Earth. However, if the students created a model that correctly represented this fact, they could not observe an eclipse due to the large distances between the objects in their model. At this point, students were forced to decide what concepts their model would demonstrate (correct scale or conditions for an eclipse), acknowledging that in the process they would lose some realism. In struggling with this issue, students developed a richer understanding of eclipses and gained an appreciation of one purpose of models—simplify the situation under study through simulation, or imitation to elucidate key concepts. Commenting on the importance of the modeling process, one student stated:

> I don't think I would have understood this process as well without the models because the five-degree tilt was just a number in my other classes. I did not understand the need for the 5-degree tilt until we saw that eclipses were happening every month!

IMPLICATIONS

Given the power of current technologies, educators must find ways of integrating 3-D technologies into learning environments to improve and deepen students' understanding of the content, to empower students with the tools of scientists, and to do so in a fashion that is financially viable and sustainable. In lab-based studies, VR technology has been shown to have great potential for learning and instruction (Dede et al., in press). However, even with the constant downward spiral of cost/perform function for the past 20 years, these technologies are prohibitively expensive to learning institutions. We need effective instructional models that take advantage of the learning potential and enabling opportunities for doing science, and doing so in a cost-effective manner that will make feasible the use of these innovative technologies. A curriculum that requires every student to have $20,000 head-mounted displays for nine hours a week and four technicians supporting the laboratory will have minimal impact on education in general. The challenge is to address questions of feasible integration. The VSS course discussed here moved in this direction by using low-end Silicon Graphics machines and moving from a lecture to a project-based course. Currently, we are teaching the course on regular personal computers (less than $2,000 a machine) using VRML freeware.

The VSS Project, at its core, involves the replacement of lecture-based instruction as the central instructional activity in an introductory astronomy course with students constructing virtual solar system models. In the VSS, from day one, students are constructing models of the solar system. Or more precisely, they constructed models of the solar system in an inquiry process to frame and answer fundamental astronomy questions. Central to the design of the course was our pedagogical commitment, which involved moving away from lectures and towards immersing students within participatory learning environments. Although there is a growing theoretical base from which to derive principles for the design of technology-based, participatory learning environments, it is essential that we provide an empirical base to ground this perspective; that is, we need to continue to examine the learning that is <u>actually</u> occurring within these contexts. To this end, we have developed our research agenda as a series of design experiments (Brown, 1992) in which we engineer various design modules that are introduced as curricular constraints and that offer new learning opportunities for our students. The interactions related to these modules are then captured using video cameras, interviews, and document analysis so that we can trace the impact of the module. The findings from this study can provide educators with an understanding of this process.

With respect to learning astronomy, it was our initial contention that astronomy education must make a profound transition from an emphasis on delivering content through large-class lectures to a focus on supporting students as they construct concrete artifacts and (in the process) build rich understandings. In terms of construction of meaning, students did not memorize astronomical concepts as self-contained entities or as facts to be regurgitated on a test. Rather, understandings emerged as ephiphenomena (or “residue”, Heibert et al., 1996) arising within their participation in model building activities. Concepts (e.g., plane of the ecliptic, relative scale) were embodied within practices in which their meaning and value were <u>actualized</u>, not simply <u>realized</u> (Barab, Hay, & Duffy, 1998). For example, the concept of relative size was not a separate activity that students developing a solar system were expected to study; rather, it was a way of defining the constraints of their virtual worlds. In this way, concepts were relegated to conceptual tools that were embodied within practice and stood in sharp contrast to their more frequent treatment as abstract, disembodied facts introduced through didactic lectures (Bransford, Franks, Vye, & Sherwood, 1989; Roupp et al., 1993). The concrete instantiation of students’ understandings into VR artifacts facilitated the development of grounded understandings, not as separate concepts stored in the learner’s brain but as distributed descriptions that were situated across and through their experiences (Barab et al., in press; Pea, 1993).

In this article, we have described and critically examined a course that engaged students learning astronomy through the building of VR worlds. Our findings indicate that this initial course was a successful innovation in which the learning of astronomy occurred through the construction of VR models. As we continue to do research and analyze the data, we will gain a richer understanding of the potential of these participatory, technology-rich contexts for supporting learning. We challenge ourselves and our colleagues to continue this exploration so that we may ground theoretical conjectures regarding the potential of these contexts in empirical findings.

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Table 1. Central Features of TRIPLE-GU.

a.	A central component of these environments is that they are technology-rich, integrating technology as a tool for facilitating inquiry and/or other forms of authentic practice.
b.	These environments must provide an opportunity for students to inquire into the phenomena they are learning, and not simply receive information about the phenomena.
c.	Rather than telling students about practices, our environments are designed to support students in participating in domain-related practices.
d.	These environments are intentionally designed to support the process of learning.
e.	It is our intention to establish rich environments (studios, workshops, construction spaces) where students work collaboratively, not isolated classes or places to listen to lectures.
f.	These environments are intended to immerse students in a context that grounds their understandings to meaningful activity.

Table 2. The Pedagogical Issues Investigated in This Study, Framed as Research Questions.

Issue	**Research Question**
Role of Teacher	What was the role of the teacher in this participatory learning environment?
Group Dynamics	What were the dynamics that formed in each group?
Modeling Process	How did models facilitate students learning astronomy?
Resources	What were the resources, specifically student-developed inscriptions, used?
Technology	What was the role of technology, and did learning the technology interfere with learning astronomy?

Figure 1. Screenshot of the cylinder created in CosmoWorlds.

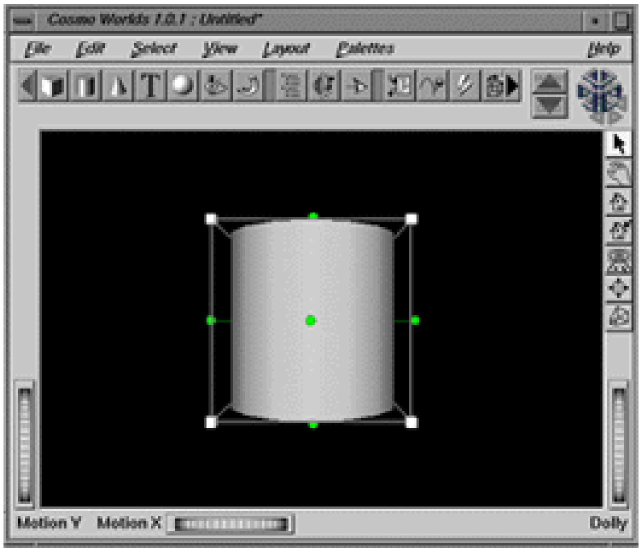

Figure 2. Screenshot of the Earth Object with the 23-Degree Tilt Being Added.