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Virtual Solar System Project: Building Understanding through Model Building

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Abstract: In this manuscript we describe our introductory astronomy course for undergraduate students in which students use three-dimensional (3-D) modeling tools to model the solar system and, in the process, develop rich understandings of astronomical phenomena. Consistent with our participatory pedagogical framework, it was our intention to establish a context that supported students in carrying out scientific inquiry using virtual models *they* developed. The progression of our thinking and the course curriculum has been grounded in a series of "design experiments," in which we develop entire courses, do research, and cycle what we are learning into the next iteration of the course. In this manuscript, we use field notes, portions of case studies, interview data, artifact analysis, and excerpts from previous manuscripts to situate the reader in the actual happenings of the course. Focusing primarily on the dynamics of the earth–moon–sun system, we illustrate the modeling process and how learning evolved in this context. In general, we found that 3-D modeling can be used effectively in regular undergraduate university courses as a tool through which students can develop rich understandings of various astronomical phenomena. Additionally, we found the design experiment approach to be a useful strategy for supporting course design that was both theoretically and empirically grounded.© 2000 John Wiley & Sons, Inc. J Res Sci Teach 37: 719–756, 2000

Introduction

With respect to learning astronomy, we believe that astronomy education should make a 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. Inquiry into astronomical phenomena has always been difficult in astronomy

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courses because the phenomena are so far out of reach—students obviously cannot visit the sun or moon. However, the power of the modern-day computer to do computational modeling and desktop virtual reality (VR) has created new opportunities for inquiry approaches to learning (Sabelli, 1994; McClellan, 1996; Stratford, Krajcik, & Soloway, 1998) and teaching astronomy (Barab, Hay, Barnett, & Squire, 1998; Hay, Johnson, Barab, & Barnett, in press). These technologies allow students to enact basic astronomy concepts (e.g., tilt of the earth, phases of the moon, frequency of eclipses) into dynamic, three-dimensional (3-D) scale models. These models can then serve as a vehicle for students to pose inquiry questions as they come to understand the dynamics of the solar system. For example, students might ask themselves when an eclipse will occur, or what would happen if they changed the orbital period.

Over the past 2 years, we have been exploring the potential use of 3-D modeling tools to create learning environments in which students of all ages can build virtual worlds and, in so doing, learn a great deal about topics related to theater, government, and astronomy (Barab, Hay, & Duffy, 1998; Barab, Hay, Barnett, & Squire, in press). The purpose of this article is to describe our introductory astronomy course for undergraduate students in which students use 3-D modeling tools to model the solar system and, in the process, develop rich understandings of astronomical phenomena. We have engineered our research and development as a series of "design experiments" (Brown, 1992) that involve introducing innovations into the classroom and examining how these innovations impact the learning process. The implications of the findings are then cycled back into the next iteration of the course.

For this paper, we use field notes, portions of case studies, interview data, previous manuscripts, and artifact analysis to describe the process of modeling and how students participating in this process learn astronomy. More specifically, we begin with a grounded discussion of the course evolution, describing the trajectory of our curriculum over the last 2 years. Case study reporting of one student's experience is then presented so as to contextualize the reader in terms of the course process. Following this case study, we then illustrate how through modeling the earth–moon–sun system students learn about phases and eclipses, and how students use their models to visualize astronomical phenomena. From here, we focus in on student collaboration, using the concepts of orbital motion and phases of the moon to illustrate the knowledge diffusion process in our course. Results are then discussed in terms of the usefulness of the participatory framework for supporting learning and modeling as a form of distributed cognition.

Background

Technology-Rich, Inquiry-Based, Participatory Learning Environments

Many educators have argued that the lecture format concentrates on memorization of factual information and promotes the development of superficial understandings (Ruopp, Gal, Drayton, & Pfister, 1993; Roth, 1996), inert knowledge (Whitehead, 1929; Cognition and Technology Group at Vanderbilt, 1993), and does little to correct the many alternative conceptions that students have regarding the foundational concepts of science (Pfundt & Duit, 1991; Wandersee, Mintzes, & Novak, 1994). The film, *A Private Universe*, presents a dramatic example of university students' alternative conceptions about basic astronomy concepts (Pyramid Film & Video, 1988). Twenty-one of 23 graduating seniors interviewed during a Harvard University commencement ceremony were unable to provide an accurate scientific explanation of the cause of the seasons or phases of the moon. Numerous other studies have documented students' alternative conceptions regarding the dynamics of the earth–moon–system (e.g., phases of the moon, eclipses, line of nodes) (Baxter, 1989; Vosniadou, 1991; Schoon, 1993; Skam, 1994; Sneider, & Ohadi, 1998). Further, it has been argued that such approaches have the ancillary effect of stifling creativity and diminishing enthusiasm (Cordova & Lepper, 1996).

Partly in response to such concerns, an increasing number of educators is abandoning the predominantly didactic, lecture-based modes of instruction and moving towards more *participatory* models in which students, frequently in collaboration with peers, are engaged in problem-solving and inquiry (Papert, 1991; Duffy & Jonassen, 1992; Land & Hannafin, 1996; Roth, 1996; Sfard, 1998; Barab & Duffy, 2000; Young, Barab, & Garret, 2000). Rather than presenting instructional treatments, the goal in designing participatory learning environments is to establish rich contexts that encourage explanation and discovery (what Perkins, 1991 called *phenomenaria*) and to support students working collaboratively on the construction of personally meaningful and conceptually functional representations (Jonassen, 1991; Barab, Hay, & Duffy, 1998).

The goal of the VSS project is to establish a fertile context to support learner inquiry. The participatory learning environments that we have been developing are technology-rich and allow students to ground their understandings within their own concrete experiences (Barab, Hay, & Duffy, 1998; Barab, Hay, Barnett, & Squire, in press). We refer to these environments as technology-rich, inquiry-based, participatory, learning environments for grounding understanding (TRIPLE-GU). We view the notion of participatory learning environments (PLEs) as an umbrella term under which terms such as project- or problem-based learning can be nested and used to further clarify the particular type of PLE. These environments take advantage of emerging technologies to establish PLEs that immerse students within contexts that challenge, ground, and ultimately extend their understandings (see Table 1 for a list of the central features).

These environments are collaborative in nature, with students negotiating goals, tasks, practices, and meanings with peers (Nastasi & Clements, 1991; Blumenfeld, Marx, Soloway, Krajcik, & Soloway, 1996; Savery & Duffy, 1996). Project-based learning is one example of a participatory approach, emphasizing learning activities that occur across extended time frames, are student centered, interdisciplinary, have real-world relevance, and engage students in an inquiry process (Blumenfeld et al., 1996; Krajcik, Blumenfeld, Marx, Bass, & Fredricks, 1998). A central characteristic of well-designed projects is that underlying the work is a set of driving questions or problems, developed by the students or the instructor, that focuses and provides motivation for student activity (Blumenfeld et al., 1996; Barnett, Barab, & Hay, in press).

Table 1
Central features of TRIPLE-GU

A central component of these environments is the use of *technology* as a tool for facilitating inquiry and/or other forms of authentic practice.
These environments must provide an opportunity for students to *inquire* into the phenomena they are learning.
Rather than telling students about practices, our environments are designed to support students in *participating* in domain-related practices.
These environments are intentionally designed to support the process of *learning*.
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.
These environments are intended to immerse students in a context that *grounds* their understandings to meaningful activity.

Within a project-based learning environment, students solve problems that are typically interdisciplinary by developing and revising questions, formulating hypotheses, collecting and analyzing relevant information and data, articulating their ideas and findings to others, constructing artifacts (e.g., models), and participating in defining criteria and rubrics to assess their work (Barnett et al., in press). The interdisciplinary and concrete nature of these projects is of particular importance for astronomy education, because astronomy is a derivative science that calls upon principles and methods associated with several different disciplines. For example, Newtonian physics provides the concepts of gravitation and electromagnetism, nuclear physics explains energy transformation in stars, chemistry and geology explain stellar spectra and surface properties of terrestrial planets, and mathematics underlies all of these.

Consistent with Papert's (1991) *constructionist* pedagogical framework, much of our work involves designing projects that result in the creation of shared artifacts or products (Barab et al., 2000). It is these student-constructed artifacts that support the evolution of and are part of students' evolving understandings (Salomon, 1993). Additionally, they serve as a medium through which students engage in dialogues with peers, supporting the reflection and re-evaluation of their emerging understandings (Pea, 1993; Barab et al., in press). The rationale underlying these environments is that the task (central hub) provides an anchor around which class activity emerges (Barab & Landa, 1997). The central task and requisite work provide the motivational and conceptual framework through which meaningful inquiry can occur. This emphasis on a shareable product shifts the focus from teacher-directed instruction or even student-directed learning toward object-directed activity (Barab, Barnett, Yamagata-Lynch, Squire, & Keating, in press).

The nested relations among these three pedagogical frameworks (participatory, project-based, and constructionist) are illustrated in Figure 1. At the broadest level are participatory learning environments, with the central defining feature being that students are actively involved in their learning process. However, there are many innovative approaches to engaging students in taking ownership and being actively involved in learning. We have found project-based learning environments, with their emphasis on a defining task or project that provide the motivational and conceptual anchor, to be particularly useful for engaging students. Last, with respect to astronomy, a contructivist framework, with its concrete focus on having students build collaborative artifacts, was a particularly useful way of defining the types of project-based activities in which students can engage.

In these environments, the role of "teacher" changes from one of *telling* students correct answers to *guiding* and *facilitating* learner activity, as students engage in the inquiry process (Vygotsky, 1978; Dewey, 1963). Students are considered active participants in the learning process, setting their own learning goals (in relation to the task) and forging meaningful relations

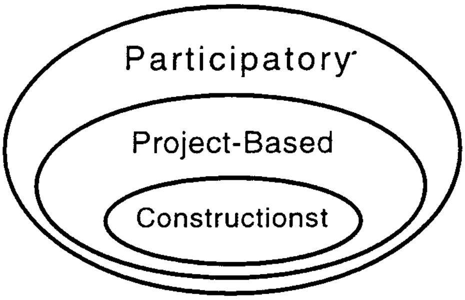

Figure 1. The nested relations among these three pedagogical frameworks.

through their experiences. This is consistent with the emergent activity structures supported through problem-based learning (Koschmann, 1996), anchored instruction (Cognition Technology Group at Vanderbilt, 1993), integrated units (Barab, 1999), and Goal-Based Scenarios (Schank, Fano, Bell, & Jona, 1994). In establishing these environments, many educators are currently exploring the potential of emerging technologies as tools to support students in, or as objects of, their student goal-directed behavior (Koschmann, 1996).

Leveraging Advanced Technologies. In general, technological advancements have made possible many new and exciting learning opportunities that support students in collaborative learning and inquiry (CTGV, 1993; Scardamalia & Bereiter, 1994; Edwards, 1995; Winn, 1995; Jonassen, 1996; Koschmann, 1996; Barab et al., 1998; Young & Barab, 1999). In particular, we have been exploring the potential of desktop VR to support participatory learning experiences (Winn, 1995; McClellan, 1996; Olson, 1998). More generally, VR has the potential to immerse the learner in various situations (the surface of the moon or the delicate strand of the DNA molecule), collaborate with people thousands of miles away (in adventure learning projects), see hidden phenomena (forces directed on an object or a tumor in a body), visualize information (the temperatures of a frontal system), or even bring museum artifacts to the hands of the learners. However, only recently have educators working with K-12 students begun to explore the educational possibilities of VR learning environments (Winn, 1995; Osberg, Winn, Rose, Hollander, & Hoffman, 1997; Dede, Salzman, Loftin, & Sprague, 1999; Hay et al., in press).

Using generic 3-D modeling construction tools, Barab and Hay (Barab, Hay, Barnett, & Squire, in press; Barab et al., in press; Barnett et al., in press; Hay, Johnson, Barab, and Barnett, in press) have been researching students building VR solar systems. In an initial project and study, high 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 (Barab, Hay, Barnett, & Squire, 1998; Hay & Barab, in press). With respect to the Virtual Solar System project, as students constructed their VR models, previous astronomical alternative conceptions were challenged, leading to the development of a more realistic sense of the relative interactions of the sun, the planets, and their moons. Consistent with other educators, we have witnessed the potential of these new technologies to support students in carrying out the practices of scientific modeling (Jackson, Stratford, Krajick, & Soloway, 1994; Lehrer, Horvath, & Schauble, 1994; Roth, 1998).

The Practice of Modeling

Current computer advances are transforming science and creating exciting new opportunities for learning about science (Sabelli, 1994; Stratford, 1997; Stratford, Krajcik, & Soloway, 1998). In particular, the methods and processes of inquiry through computational modeling bring new challenges for science educators (Jackson et al., 1994; Lehrer et al., 1994). From a learning perspective, the act of modeling allows students to engage in a design process which begins with a set of tentatively accepted theories that evolve into coherent understandings as represented in their models (Sabelli, 1994; Roth, 1996). As a result, modeling activities have become more commonplace in inquiry-based science classrooms, in part because educators have recognized that an important activity of scientists is building, designing, testing, and evaluating models of natural phenomena (Hestenes, 1992).

In contrast to showing students models designed by others, many modeling initiatives support students in constructing their own models (Jackson et al., 1994; Penner, Lehrer, &

Schauble, 1998; Roth, 1998). During this process, a ‘‘conversation’’ unfolds in which robust interactions occur among students, between students and the teacher, and among students and their model and the materials (inscriptions) of their work as they attempt to create meaning through and from their constructions (Roth, 1996). This conversation guides the students to evaluate their methodologies (how they constructed their models), their justifications (does their model reflect the real system adequately?), and their perceptions (did they recognize the true problem under study?) (Peterson, Jungck, Sharpe, & Finzer, 1987). Students move beyond simply discovering facts to be memorized and become involved in an iterative process in which their understandings inform the development of their models and the evaluation and testing of their models inform evolving understanding. These opportunities are consistent with Schön’s (1987) distinction between reflection-in-action and reflection-on-action. While the former refers to reflection within the activity, the latter refers to the importance of having an opportunity to reflect following the activity. Schön (1987) and others have demonstrated the importance of, and reflexive relations between, both types of reflection to the learning process, especially when educators support students in participatory learning environments.

An important aspect of modeling, especially computational modeling (Sabelli, 1994; Stratford et al., 1998), is that it allows students to visualize abstract concepts by creating structures through which they can explore and experiment. In a very real way, student models *distribute* cognition, providing concrete structures through which students can develop conceptually rich understandings. These understandings are, in turn, distributed acts that are stretched across the modeling process—a process that becomes a tool to examine, and is apart of, student understanding of astronomical events. Central to this line of thinking is the conviction that a learner’s understanding of any concept, process, or practice, as well as her ability to act competently with respect to these, can be attributed to, and is distributed across, the physical, temporal, and spatial occurrences through which her competencies have emerged (Pea, 1993; Salomon, 1993; Barab, Hay, Barnett, & Squire, in press). In other words, cognition is ‘‘stretched over, not divided among—mind, body, activity, and culturally organized settings which include other actors’’ (Lave, 1988, p. 1). Resources typically conceived as external are viewed as part of the system through which competent action emerges, affecting conceptions of what, how, and why one needs to know (Perkins, 1991; Cole & Engeström, 1993; Salomon, 1993).

Having powerful tools, resources, and processes through which to distribute cognition is especially relevant to astronomy learning. Astronomy is one subject in which students must gain an understanding of dynamic relationships and events that take place in 3-D space (Parker & Heywood, 1998). However, despite the 3-D nature of astronomy, most resources available to students are in the form of charts, 2-D images, textbooks, and slides. Therefore, students read (and memorize) descriptions of 3-D concepts illustrated using a 2-D medium. Given the growing power of computers and the dramatic reduction in costs, students using standard desktop personal computers are now able to construct 3-D models that transcend the flat, limited 2-D images. Hence, they are able to build understandings of complex dynamics while modeling and visualizing these dynamics in 3-D.

The Course Context

The Virtual Solar System (VSS) project is an experimental undergraduate astronomy course initially taught at a large midwestern university and now being expanded to a southeastern university as well. In the VSS course, listening to lectures is replaced by students building 3-D models of different aspects of the solar system using a virtual reality modeling language (VRML) editor (described more fully below) on average desktop personal computers. In contrast to immersive virtual reality (VR) that places students *in* the virtual world, the software being used in this course simulates a 3-D environment on a normal desktop monitor (McLellan, 1996). In other words, students are not wearing VR headsets but instead can work side-by-side and carry on casual conversation as they collaborate. The curriculum was developed by an astronomy professor, two educational psychologists, and a graduate student studying astrophysics and instructional systems technology.

The current iteration of the course requires students to build three projects with the expectation that they will model various astronomical phenomena on their computers (see the course syllabus and links to different semester student projects as well as some student papers: http://inkido.indiana.edu/a100/). These are introduced in the course syllabus passed out on the first day (see Table 2 for project descriptions).

The first step in a project is for the instructor to introduce the particular "seed" questions developed for the specific project. Student models are expected to address these instructor-delineated as well as student-generated questions related to important astronomical phenomena. The purpose of the seed questions is to help frame the development of a model around which these and other questions could can be addressed. Each group negotiates plans to answer the questions, identifies resources (textbook, WWW, and scientists), designs and builds their models, evaluates them, uses them to demonstrate answers to the initial questions, and shares their models with other groups. In addition to instructor-supplied seed questions, students are expected to develop four-to-five questions of their own that their models will address. These questions are based on their research and revised throughout the project development period.

Table 2
Course project descriptions

Project 1	Project No. 1 is to construct a *static* model of the Celestial Sphere. This project requires students to generate a static model of fundamental astronomical concepts concerning the equinoxes, the solstices, and the ecliptic and the celestial equator. The Celestial Sphere is a useful concept, first envisioned by ancient astronomers, to represent the location of the visible stars and important positions of the sun throughout the year. The goals for the students during this project are to construct a geocentric model of the earth–sun system to learn the essential astronomical terminology (e.g., right ascension, declination, equinox), to learn the causes for the seasons, and to build a conceptual base that they will use to understand future astronomy concepts. Students decide upon scaling parameters, discuss how their model compares with the real solar system, and generate viewpoints so that users can visualize the equinoxes and solstices from multiple locations.
Project 2	Project No. 2 is to construct a *dynamic* model of the earth–moon–sun system. This includes proper sizes, distances between objects, surface features, correct tilts of the bodies, and correct rotation and orbital periods. In addition, students are to provide a cut-away view or a transparent view that shows the interior structure of the sun, earth, and moon. This project extends the conceptual richness of the first project because students concern themselves with the scale of the system, orbital motions of the three bodies, and conditions for lunar and solar eclipses. The students are also asked to compare their model with the real earth–moon–sun system and report any discrepancies (e.g., scale, orbital speeds) between the two. In contrast to the static depiction of the Celestial Sphere in Project 1, this project requires students to model the complex dynamics as they animate the objects they create.
Project 3	Project No. 3 is to construct a *dynamic* model of the entire solar system, including both the terrestrial planets and Jovian planets. Specifically, students are expected to make a model of the sun, eight planets (Pluto and Charon 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.

Table 3
Seed, base, and enrichment questions for the earth–moon–sun system

Seed questions: Initial questions to start the project off
1. What is the relative size and scale of the earth, moon and sun?
2. What are the conditions necessary for phases of the moon and eclipses?
3. How does the sun shine?
4. What are the differences and similarities between the earth, sun and moon interior and atmospheres?

Base questions: Questions that students answer after or during the construction of their models
1. Where is the moon when it is full, new and quarter in relation to the earth?
2. What is rotation and revolution rate of the moon?
3. What effect does the moon's revolution and rotation rate have on its appearance?
4. What is the ecliptic, and what is the moon's position relative to the ecliptic?

Enrichment questions: Questions that are used in our ''thought experiments''
1. What is the difference between the sidereal and synodic month for the moon?
2. What is the line of nodes, and what does it tell us about eclipses?
3. Does the moon have seasons?
4. Does the sun set when viewed from the moon?
5. When you are on the moon does the earth have phases?
6. How long is a day on the moon?

Example: Student generated questions
1. How often do we get a solar eclipse?
2. How big does the moon look from the earth?
3. What would happen to the earth's seasons if the earth was tilted on its side?

A second set of instructor-developed questions, we call ''base'' questions, are introduced to each group, addressable with the same model, and serve the purpose of filling out the curriculum. However, unlike the seed questions that are introduced to students before the model constructing process begins, base questions are presented to groups when they are ready at the discretion of the instructor. Lastly, we have also developed a series of ''thought experiments,'' in which students work to answer enrichment questions using their models, probing and challenging the depth of their understandings. Unlike the seed and base questions, these questions are not introduced to each group, but are available with the instructor for groups that he perceives as capable of addressing, and potentially benefiting from, more advanced problem solving (see Table 3 for a listing of seed, base, enrichment and some examples of student-generated questions).

Each project has four concluding activities. First, teams create a joint paper describing the features of their model. Second, each student presents and explains their team's model to students from other groups in a CAVE 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 engage in a group presentation, in which they demonstrate the functionality of their model to the entire class, using an overhead display in the regular classroom. Fourth, students write individual papers that compare and contrast their projects 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 will demonstrate 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).

Enabling Technology. The creation of computational models has traditionally been the work of technologically sophisticated graduate students and scientists and well out of the reach of university freshman. Three-dimensional modeling tools in general, and VR editors in particular, have formed a bridge between the limited technology skills of our undergraduate students and the processes of computational modeling. Specifically, our students create models to address questions using virtual reality modeling language (VRML), which is a language similar to HTML in that it establishes a common standard for making VR easily distributable over the Internet. In our course, students use a VRML editor[1] which 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. Similar to the manner in which current HTML editors automatically generate code, these VRML editors allow the users to simply drag a sphere from the toolbox into the workspace and size it directly, instead of typing in scripts. While adding a color or positioning the object anywhere in the 3D space would have taken multiple lines of code, this procedure takes the user of an editor only a few clicks and drags (see Figure 2). These direct manipulation editors afford students the opportunity to quickly develop a dynamic 3-D model of the solar system as part of an inquiry process.

Methods

This Study

For this study, primarily naturalistic inquiry methodologies involving both quantitative and qualitative data have been used to gain a holistic vision of the semester-long Virtual Solar System (VSS) course (Guba & Lincoln, 1983; Stake, 1983). Rather than segmenting out various course aspects and examining them independently, we have attempted to develop a holistic view of our intervention, examining the effect of curricular requirements on learning within the full context of the course. More specifically, our research agenda has been consistent with Brown's (1992) notion of "design experiments," in which entire courses are designed (as opposed to constrained laboratory contexts) and then the impact of innovations on the learning process is examined. Lessons learned are then cycled back into the next iteration of the course, in which we examine the impact on the learning process. Because design experiments develop theory in practice, they can lead to interventions that are trustworthy, credible, transferable, and ecologically valid (Roth, 1998).

Data were collected over a 2-year period through direct observation and field notes, the use of multiple video cameras directed at individual learning groups in a particular classroom, interviews with students and instructors, document and artifact analysis, and retrospective recall analysis. Consistent with the work of Roth (1996), these efforts collected data that: (a) documented practices (e.g., tool use, problem solving, student inquiry) and resources (e.g., concepts implemented, tools); (b) captured the discussions among students and between students and teachers; (c) documented the progress of student projects; (d) traced the same students, artifacts, actions, and procedures over time; and (e) 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

[1] In the VSS course, students have used either Cosmo Worlds from CosmosSoftware (http://www.cosmos-foftware.com) or VR Creator (a free product) from Computer Associates (http://www.cao.com). Both are linked to the class homepage listed above.

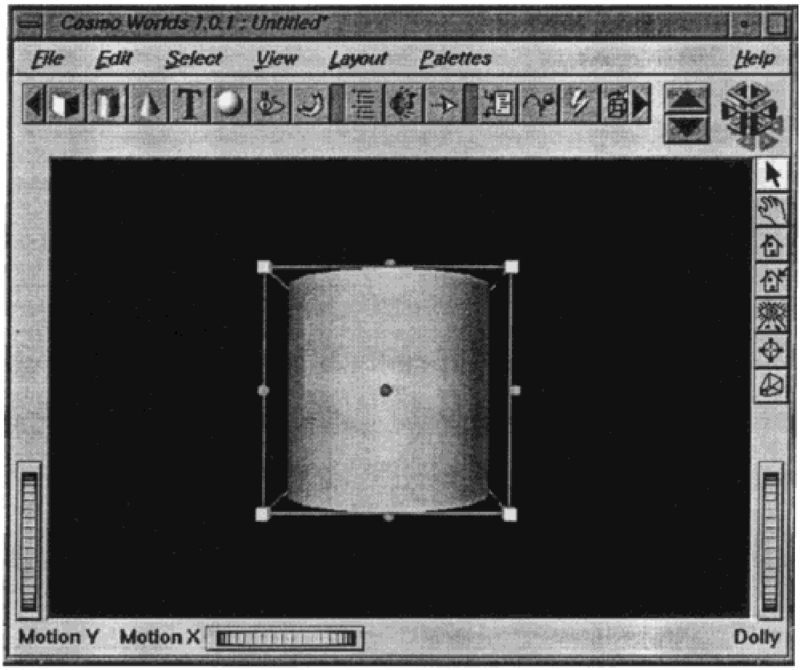

Figure 2. Screenshot of the cylinder created in Cosmo Worlds.

increasingly focused data collection and analyses. In constructing and triangulating interpretations (Lincoln & Guba, 1986), we used field notes, interviews, document analysis, previously developed case studies, and the three databases described below.

For the initial pilot (8 males, 6 females) and the first two semesters of the course (spring 98, 8 males, 2 females; summer 98, 6 males, 3 females), we had one researcher and an accompanying video camera assigned to each group of two to three students. Researchers attended all of the undergraduate classes (10 three-hour classes in the pilot, 25 one-and-a-half hour classes the next semester, and 15 two-hour classes over the summer), continually maintained notes, and when appropriate, posed questions to validate observations. We also conducted semi-structured interviews with students and teachers in each iteration of the course and we conducted semi-structured interviews probing student understandings after the completion of the course. Pre–post interviews were also carried out with the students in the spring 99 courses (13 males, 17 females), although a researcher was not present for all these course meetings.

These data collection efforts resulted in a large corpus of the data, including seven case studies, over 200 videotapes of course interactions, interviews conducted before, during, and after the course, reams of field notes, numerous student-produced resources and artifacts, and on-line databases containing approximately 3,500 "episodes" of coded activity. With respect to the databases, each episode, minimally, contained information about the issue at hand (theme), who the initiators were, who the participants were, what practices the initiators were engaged in, and what resources were being used (Barab, Hay, & Yamagata-Lynch et al, in press). Lincoln and Guba (1986) recommended triangulation as one means of increasing the credibility of interpretations derived from naturalistic interpretations. Interpretations were triangulated using multiple data sources, including observations, interviews, document analysis, case studies, learner debriefing, and analyses of referential materials.

Pre–Post Interviews

For the pre–post interviews, the interview questions were semi-structured, consisting of nine questions that covered a wide range of astronomy concepts typically covered in the traditional introduction to astronomy courses (Keating, Barnett, & Barab, 1999). The questions were derived from the alternative conception research (Sadler, 1987; Treagust & Smith, 1989; Comins, 1993; Schoon, 1993), and from consultation with faculty members from the Astronomy Department at Indiana University. Two example questions are: (1) Compare and contrast the differences and similarities between a full moon and a lunar eclipse, and (2) What causes the seasons of the earth?

The fifteen 30-min pre-interviews were videotaped and conducted during the first 2 days of the class to capture students' understanding of astronomical phenomena prior to their constructing 3-D models. Students were provided a set of spheres for manipulation and a white board for drawing to demonstrate their explanations. The interviewer asked probing questions to establish the depth of students' conceptual understanding. The post-interviews were conducted during the last week of the course, and typically lasted 30–60 min. Again, the students were asked to verbally express their understandings and were encouraged to manipulate spheres or draw on the available white board.

Assessing student conceptual growth involves extensive viewing of the videotapes followed by analysis and coding of the transcribed interviews. Student responses were scored using a rubric based upon the categorization scheme used by Simpson and Marek (1988) and Muthukrishna, Carnine, Grossen, and Miller (1993) (see Table 4 for a model rubric—each level is then contextualized to specific content, e.g, celestial sphere, eclipses, etc).

Selecting Themes and Building Interpretations

In presenting the data related to our series of design experiments on the VSS course we began reviewing our large corpus of data (described above) and additionally reviewed the interpretations described in previous manuscripts (Hay & Barab, 1998, 1999; Barab, Squire, & Barnett, 1999; Barab, Hay, et al., 2000; Barab, Barnett et al., in press; Barnett et al., in press; Hay et al., in press). From these data and from prior analyses, as well as our understanding of what would represent a useful account of a design experiment, we focused on (a) the course evolution and (b) how the course supports learning. First, we selected data and interpretations related to the course evolution. This began with an analysis of the different syllabi used each semester and determination of what had changed. From here, we searched back through the field notes and other data to identify the justifications for these changes as well as data sources to illuminate the justifications.

With respect to how the course supports learning, we settled on three themes that have become central to the course activity. First, we focused on illuminating for the reader what the inquiry cycle looks like in practice. We felt that an appreciation of the inquiry cycle is necessary if the reader is to gain a "feel" for the course experience. From the seven case studies generated, we selected portions of data from two groups in the summer 1998 course. It would be inappropriate to say that these descriptions were representative of all students' stories; however, our data suggest that these experiences were not somehow unique trajectories. In fact,

Table 4
Example rubric used in analyzing student understandings of eclipses and phases

Score	Category	Response
0	No conception	Students are unable to articulate a response to the question.
1	Confused	Students confuse the positions of a full moon, new moon, and lunar eclipse. Students have an alternative framework. Students lack knowledge of basic concepts (moon's orbital tilt, rotation and revolution rates), and proper terminology.
2	Incomplete/inaccurate understanding	Students have an alternative framework concerning either the positions of objects for eclipses and have merged their understanding with the correct scientific perspective (believing that a lunar eclipse occurs because of the earth's shadow being cast by its clouds). Students are also unable to articulate the difference between a full moon and a lunar eclipse.
3	Partial understanding	Students know the basic concept that the moon's orbit is tilted at five degrees, but do not discuss the line of nodes or its importance for lunar eclipses. Students can point out the positions of a lunar eclipse and solar eclipse, but struggle to articulate the difference between a full moon and lunar eclipse.
4	Complete Understanding	Students understand the importance of the 5-degree orbital tilt of the moon. They know about the ecliptic and the moon's orbital plane, and that when these two planes intercept they form the line of nodes and that when the earth, sun and moon are on the line of nodes an eclipse occurs. Further, the students can point out the positions of a lunar eclipse and a solar eclipse, and can articulate the difference between a full moon and lunar eclipse.

throughout the manuscript we have continually selected, when appropriate, data from the ''red'' group so as to provide the reader with a more in-depth (as opposed to shot gun) feel for course activity—both the positive and negative. The tension of breadth and depth in reporting qualitative data is nothing new, and we have attempted to air on the side of continually cycling back to one group while at the same time bringing in other group data to the discussions so as to suggest more representative accounting.

Following our descriptions of the inquiry cycle, we then focused on the multiple ways that modeling was used to support reflection and learning. The goal here was to show how model building supported learning, both in terms of the constructing of their models and in reflecting on the constructed models. Third, given that we have attempted to support the development of participatory learning environments in which students are expected to collaboratively direct the learning process, we focused on the diffusion of knowledge. We have extensive data regarding the role of students and of the instructor, including video recordings, field notes, and interview data. It was through an examination of these data that we built our interpretations in this section.

More generally, in all sections we examined field notes, interview data, pre–post interviews, and used the database to identify re-occurring themes that appeared central to course interactions. These multiple sources of data allowed us to triangulate our interpretations. As themes were identified, we would select various subjects (students, instructor), tools, practices (tool- and concept-related), student productions (e.g., projects developed), and conceptual understandings (e.g., understandings of eclipses, instructor practices, project expectations) and then further used the database and field notes to identify their historical development throughout the multiple courses. Based on examination of these multiple sources of data we selected these three issues (the inquiry cycle, leveraging the modeling process, knowledge diffusion) as central to this paper, built interpretations around each issue, and selected relevant data sources to illuminate our points. Member checks with the course instructor and former students were used to further validate that these were indeed representative and that our interpretations were consistent with their experiences.

Curricular Evolution

Learning the Technology

Although the basic tenets of the curriculum have remained the same since the course prototype, our series of design experiments have led to numerous curricular revisions. One of the major challenges of the initial course was the tension between learning astronomy and the simultaneous technical mastery of the software (Barab, Hay, Barnett, Squire, in press; Barab, Barnett, et al., in press). Central to our pedagogical commitment was the belief that learning technology should be contextualized as part of the model building process. As such, we did not want to take the first week to didactically teach students how to use the technology and then begin introducing astronomy at week 2. However, in the first spring semester, the first project immediately immersed the students in modeling the complex orbital dynamics of the earth–moon–sun system and did this at the same time that they were learning the technology. Students were overwhelmed, trying to attach "viewpoints" in their model (viewpoints allowing the viewer to experience the VR world from various perspectives and locations) to objects that would be constantly changing their location in 3-D space.

The following discussion taken from Barab, Squire et al. (in press) illuminates students' frustrations. In this dialogue, Kurt and Mandy are struggling to create and animate viewpoints to show the moon's eclipse.

> Kurt: So you didn't get it back to the right place?
>
> Mandy: What happened there? I don't understand. Is that the earth and moon?
>
> Kurt: I don't know. Why do these things keep moving? Why don't they just do it on the Y [*axis*]? It's real frustrating.... Can I drop this class? [*Then, to the computer*] C'mon please?... Very frustrating. CosmoWorlds won't do anything I tell it to do.

In this segment, Kurt knows what he wants to do, but his inability to use the tool is interfering with his ability to build his model and demonstrate astronomical concepts.

To address student problems in dealing with the dual problems of technology and astronomy, in the second semester of the VSS course we added the Celestial Sphere as the first project. This has helped address student frustrations because the model is relatively static, providing an anchor point from which students can gradually build their technology skills. In contrast to students being frustrated by the complexity, we have observed numerous instances in the recent course where students experimented with the technology, even adding more complex animations to their Celestial Sphere project. As a result, when they begin modeling the orbital dynamics of the earth–moon–sun system, they already have a base of understanding of the technology that lessens the dramatic learning curve that emerged in the spring semester (Barab, Hay, et al., 2000).

Teacher to Student Owned Curriculum

In the first course, students were supplied a description of model expectations and a list of 60 questions from which the final examination would be derived. In a prior analysis we concluded, "the model description and the examination questions, in essence, provided structure for the students, but relieved the students of formulating good research questions to explore through their models and limited the inquiry process" (Barab, Barnett et al., in press, p. 15). This lack of ownership and inquiry was evident when the students came to the professor with the list of unanswered questions (from the initial 60) and asked for explicit answers. These types of observations, coupled with our interview data, signified to us that students were using these questions in a non-inquiry-based manner. Instead, they served as a guide in determining which facts should be memorized for the test. In one student's words, "I have been so focused on my model that I have to stay up all night and memorize answers to the questions."

In the current course, we have abandoned the explicit description of what the model must include as well as the list of questions. Instead, the instructor uses a small set of pre-determined and a larger number of student-developed seed, base, and enrichment questions to support students in developing their own model constraints. This curricular evolution was based on the results of our initial design experiments and has changed the professor's ability to answer the question, "How good do I have to make the model?" In the first course, it was a rather arbitrary judgement based on the professor's assessment of what the students could do in the given time frame. In the current courses, the instructor stated, "What are you hoping to learn from your questions? . . . It should be good enough to answer the questions" thus, turning the question into an opportunity to further encourage the inquiry process. Or, when students were confronted with challenging astronomy concepts, the instructor would ask the students, "what does your model say?" When the models were not built in a manner to answer the question, we saw periods in which the instructor would ask the students what would need to be added to the model to answer the question. It was in this fashion that students were supported in evolving their models without them losing their feelings of ownership.

By placing increasing responsibility in the hands of students, the course was able to move project ownership onto the students. As a result, students were not only responsible for defining how they would meet the course expectations, but also became partners in determining their course expectations—shifting the instructor's role from gatekeeper to facilitator/collaborator (Barab, Cherkes-Julkowski et al., 1999). In the first semester there were over a dozen 15-min plus lectures, while in the current course there were under six. However, we did see twice as many just-in-time lectures in which the instructor shared his expertise about issues of direct relevance to student models as opposed to the first semester in which his lectures were based on syllabus-defined topics. For example, in the following segment taken from Barab, Squire, and Barnett (1999) illustrates how the instructor (Instr.) seizes the moment to introduce Bode's Law and some of the history of science to the students.

> Dave: There's so much distance between Mars and Jupiter.
>
> Instr.: Nothing stops you from putting an asteroid in there. It would be more realistic . . . You know Bode's law, they're nicely distributed.
>
> Dave: That would be too easy.
>
> Instr.: That's what led to the discovery of the asteroids. [Marty, who is working on creating asteroids for his model, turns from his computer located across the aisle to listen.] Well, actually, it was coincidental. But they, an international team, were searching for another planet between Mars and Jupiter because Bode's law says there should be one there. But then the first discovery was accidental by—someone not in the project.

Marty: What was there?
Instr.: Ceres, then all the asteroids. All the minor planets—they are right there where there should be a planet.
Marty: All of them?
Instr.: No, there were four of them. And we don't know exactly why. We don't know why a planet didn't form.
Marty: Why?
Instr.: Well, it's hard to say. The planets are spaced in a certain way. When people realized this, they said, wait, we're missing one there. They had enough faith in the law that they started looking for it. While they were looking, some Italian discovered it.

The central characteristic of the just-in-time lecture is that the instructor's comments are primarily emergent, based on student activity. While in the initial course there were many scheduled lectures, in our current course we view it much more of the instructor's job to work collaboratively with students, and to be sensitive to those moments when his expertise is useful and relevant to the group's modeling activities or situated interests.

Learning Through the Design Process

Another related curricular change was in terms of the framework for building models. The nature of the course changed from creating models as one would build a model car to display on a shelf into building models in the way a scientist would within a cycle of inquiry. Previously the instructor developed detailed diagrams and descriptions of student work and students were done when they adequately represented these diagrams. In the current course, students have no explicit model and instead use their questions as guides for model design. Thus, students are now engaged in the scientific inquiry process of problem posing, formulating, solving, and reflecting through the construction of their astronomical models. Further, at the completion of the model in the initial semesters, students would be done with the project and at the next class period they would begin work on the next model. Currently, at model completion, students in the current course are given additional course time to use the model to reflect on their questions, to compare their models with other students, and to generate any additional questions that can be answered through their model.

Simultaneously with learning the value of design for supporting inquiry from our empirical observations, we also became immersed in the learning by design literature (Penner et al., 1998; Roth, 1998; White & Fredrickson, 1998). As a result, Hay and Barab (1999) developed a pedagogical model, the Computational Science of Inquiry Cycle (CSIC), for supporting students in engaging in inquiry through modeling (see Figure 3). Taken as a whole, the goal of these five steps is to engage students in a CSIC that guides them to answer fundamental scientific questions in an authentic and powerful manner. This model was collaboratively built with the instructor and became a part of the informal and formal expectation for class activity. Reframing student design work in terms of the inquiry cycle supported a transition from modeling as primarily a "hands-on" activity to modeling as a "hands-on, minds-on" activity.

As the projects became less replication tasks (as in course 1) and more design and inquire tasks (as in course 4), we created more opportunities for students to reflect on their work. This has primarily consisted of three types of activity to support student learning. First, due to the projects being structured as part of the inquiry cycle, students have increased opportunity for reflection-in-action as the modeling process unfolds. Second, we have incorporated "thought experiments" in which students at various points in the modeling process are stimulated to use

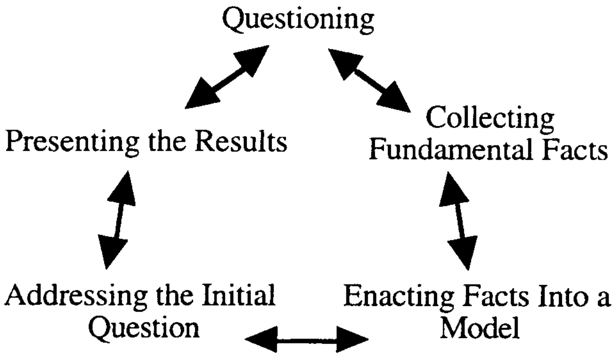

Figure 3. The Computational Science Inquiry Cycle pedagogical framework.

their models to support inquiry into instructor-posed challenges. Third, students are encouraged to reflect-on-action, using their models to visualize and understand complex astronomical relations. Given the recursive cycle of inquiry, there are no hard-and-fast lines dividing these three types of activity. However, for presentation purposes, we elaborate on each of these activities below in the "Leveraging the Modeling Process" section.

From Local to Private and Public Activity

In watching students benefit from various types of course activity, we developed a growing appreciation for supporting private activity (individual work), local activity (group work), and public activity (class presentations) (Lampert, 1990, Hall & Rubin, 1998). Similar to Lampert's (1990) classroom, these activities are not uncorrelated, but are reflexive in that each activity informs and changes the others. For instance, as part of the modeling process each individual member of a team is assigned specific modeling tasks by their team to include in their models (individual activity). However, to incorporate the individual work into their models requires discussion and negotiation among the entire team (local activity). As a part of this discussion, the team must decide how they will present a clear and coherent description of the ways in which their model demonstrates certain astronomical concepts to their peers (public activity). The comments and criticisms received during the public presentation then inform their individual papers (individual activity) as well as their group papers (local activity).

The structures to support student collaboration have been refined over the past 2 years based upon our research experiences. In the initial course structure, our activities (except for the final examination) focused primarily on supporting collaborative activities at the group (local) level. Although, there was much variation in group dynamics, we did notice certain commonalities among groups in the initial course. For instance, each student was expected to present their models to members from the other student teams. However, this approach proved problematic in that individual members of a team tended to specialize in certain aspects of the modeling process (i.e., focusing on planetary dynamics or interior structure of a planet). This division of labor typically led to students developing a deep, but rather focused, understanding of a limited number astronomical concepts. For example, during one round of post-test interviews, several students could not describe the composition of Jupiter as shown in the excerpt below from Steve's post interview first reported by Barab, Hay, et al. (2000):

Interviewer: Could you describe to me the structure of Jupiter? That is, what is the composition of Jupiter?
Steve: Hmm, good question.
Interviewer: Did you model Jupiter? Or was that your partner?
Steve: She did the work for that. I don't really know. I think it has gas, rocks. I know it has clouds. Well, hmm, I remember reading something about Jupiter being Hydrogen. I remember, Igor [the instructor] saying that if Jupiter was a little bigger it would be a star. There you go.

In addition to student specialization, we also noticed other similarities when we compared groups of two or three students. While groups of two seemed to share the workload more often, groups of three were frequently dominated by one leader and also had another member who was the "odd woman out." The team leaders usually submitted the best papers and generally had more thought behind their arguments than did students who played a more secondary role in the development of projects (see Barab, Hay, et al., 2000). Additionally, leaders clearly displayed the highest degrees of understanding on those project aspects that they were responsible for modeling. In our current course iterations we are emphasizing groups working in dyads, and our next round of research will focus on whether groups of two are more optimal for this type of learning environment than are groups of three.

In response to these and other observations, we have developed structures to increase individual accountability in terms of being able to articulate the astronomy concepts their entire team modeled. This includes the individual presentation to another group, in which one member from each team is responsible for showing and describing all parts of their team's model to other teams. Besides this public activity structure, we are also requiring students to write individual papers in which they compare their team's model to other group's models. In observing the value added as students critiqued each other's models, we are moving toward developing a scientific publishing community in which students review other student papers and models, judging them on how well they described their model's strengths and weaknesses and how their model illustrates certain astronomical concepts. This further blurs the distinction between public, local, and private activity, using public activity as a motivational and informational tool for local and private activity.

Supporting Learning

Issue 1: The Inquiry Cycle

Hay and Barab's (1999) computational science inquiry cycle (CSIC) pedagogical approach provides a framework for engaging students in the modeling process (see Figure 3). In illuminating how students learn through the modeling process, this section describes how a student team engages in the modeling process and, through the process, develops an understanding of astronomical phenomena. In this example, we follow a student team, whom we will call Team Red, from the summer 1998 VSS course as they attempt to demonstrate the differences between sidereal [viewing astronomical phenomena from the distant stars] and synodic [viewing objects with respect to that object] time. Understanding sidereal and synodic times are particularly challenging concepts because it requires students to look at the same phenomenon from different spatial locations.

In the first step of the CSIC, a driving question is developed to focus students on a problem specific to the curricular goals. This question establishes an authentic goal that drives students during the model-building process in pursuit of an answer to their question. Consistent with CSIC framework, Team Red began their modeling process by examining the seed questions. The seed question of interest in this example is, “What is the difference between the sidereal and synodic orbital periods of the earth?

During the second step, students conceptualize the model that they need to build, and gather the information and resources required to complete the model. In response to this seed question, Team Red developed a plan of how to best represent the differences between sidereal and synodic time. However, to fully develop a plan of attack the Team needed to conduct research in order to become familiar with the concepts of sidereal and synodic time. In the dialogue below we see Taro and Todd engaging in a discussion about what sidereal and synodic times are:

> Todd: So I did some of the reading last night. You know about how we need to construct a model that demonstrates the astronomy concepts. That is not going to be easy.
> Taro: So what is sidereal time?
> Todd: Isn’t that the 29.5 days or 29 days?
> Taro: What is the definition of it?
> Todd: Yes, there is a standard definition for it. It is the time it takes… [pauses looks at his current model]
> Taro: [Points out the definition in their textbook]. I think this is a simple definition.
> Todd: Ok, [looking in his textbook] here sidereal period. It is the time it takes for the earth to orbit around the sun with respect to the distant stars.

The above discussion continues for an additional 20 min, with Taro and Todd discussing the differences and similarities between sidereal and synodic time. At the conclusion of this discussion Todd and Taro begin to formulate a design plan to demonstrate the sidereal and synodic period.

Once students collect the data, they are ready to move onto the third step in which they enact assembled information into their model. At this stage, students also assess the functionality of their model, revising their model until it operates to meet their goals. Addressing the initial question is the fourth step in the process. During this phase, students build in procedures to use their model for visualizing data to highlight relationships that are critical to addressing their original question. Todd and Taro implement their plan after consultation with the instructor.

> Todd: Ok, we need to show the difference between sidereal and synodic time. Here is what I am thinking. Sidereal time is with respect to the distant stars. So what I am thinking is putting a camera here [points to his model to show that he wants to place a viewpoint above the earth–moon–sun system].
> Instructor: Why do you want to put it there for sidereal?
> Todd: Well,… because, that would be the same as a far away star I think.
> Instructor: Sounds good. Go for it.

Todd, places the viewpoint in his evolving model, but then grows unsure about how to demonstrate the orbital synodic period of the earth and how to represent it in their model. After consulting with his teammates a plan is devised to represent the synodic orbital period of the earth. In the following dialogue Todd, Taro, and the instructor discuss where to place a viewpoint to demonstrate the concept:

> Todd: Ok, I am confused again. I have this camera [points to his camera that will show the sidereal period of the earth]. But, I am not quite sure where to put one for the synodic time.

Taro: You need to place it on the earth.

Instr.: Why does the camera need to be placed on the earth?

Taro: Because it is with respect to earth.

Todd: Ok, wait a second, let me get this straight, synodic period is always relative to the earth.

Taro: Depends what synodic time you are looking at. For the earth you put it on the earth, for Jupiter's you would put it on Jupiter.

Instr.: So, the synodic time you are looking at is always with respect to the object you are standing on. In your case the earth.

Todd: So I put the camera on the earth and bingo, synodic time.

During the fifth and final step, students answer the driving question that served as the catalyst for their efforts, presenting their findings to their peers and reflecting on the limitations of their models. The presentation of the results involves a warrant (explaining how the data visualization addresses their question), and a backing (explaining why the warrant should be accepted as credible evidence) (Toulmin, 1958).

At the conclusion of Team Red's model construction process they must explain and justify how their model demonstrates sidereal and synodic time and if their model has any shortcomings as demonstrated in the below excerpt from their final paper:

> The second model was created with the intention of demonstrating the sidereal and synodic periods of the moon orbiting the earth. However, as this model is not perfect by any standards, one could not see its purpose when observing without explanation. Like the first model, there appears a large cylindrical plane (ecliptic), two smaller cylindrical planes (moon's revolution plane around the earth), and the yellow ball in the center (sun). There are also lines that show where the moon would end up after a sidereal period and after a synodic period.

Engaging in the entire modeling process enabled Team Red to construct a model that represented the earth's sidereal and synodic orbital periods, challenged the students to ask appropriate questions and use their model as a visualization tool to help them understand astronomical phenomena.

Another example of the power of the CSIC framework is evident when one examines Erica, a student in the summer 1998 semester, who was working on a different question related to the second project: How many eclipses occur each year, and why? One common hurdle for many of the teams in understanding the dynamics of the earth–moon–sun system was that prior readings and experiences suggested that lunar and solar eclipses are rare events; however initial models frequently showed that eclipses were occurring every month. As such, students were prompted by their own experiences and by the instructor to determine why the discrepancy existed. The following dialogue shows Erica's confusion after observing her earth–sun–moon model in action:

Erica: Igor (the instructor), we have a problem here. [Keith is watching and listening to the conversation]

Instr: What is going on? [Erica runs the model and the instructor watches along with the entire team]

Erica: See, it looks like an eclipse happens every time the moon goes around the earth.

Instr.: Does this match with your everyday experience?

Keith & Erica: [shake their heads no].

Instr.: Ok, it looks like you are missing something in your model.
Erica: Which is?
Instr.: Ok, I suggest that you look up the line of nodes. There is a nice discussion of it in your book. Once you read it, call me back and we can discuss it.

Upon reading about and discussing the line of nodes with her teammates and the instructor, Erica concluded that they had forgot to include the five-degree orbital tilt of the moon relative to the earth which prevents an eclipse from happening every month (see Figure 4a). By her model directly contradicting her experience it forced Erica to explore additional concepts that strengthened her understanding of astronomy. This was not an uncommon experience for students in the VSS course, in that some of their understandings became apparent during the model construction process (enacting facts in the model) while others became apparent when their models were used as a visualization tool to address the initial question.

Erica and her team began the visualization stage by asking how they could represent the line of nodes in their model. Erica suggested that a visual depiction of the line of nodes in their model would better demonstrate why eclipses do not occur every month. Building on this new information, the team inserted a long thin green cylinder in their model to represent the line of nodes (see Figure 4b). Then by running their model they could observe when an eclipse would occur by simply waiting until the earth, sun and moon were aligned on the line of nodes. It was this model that was later presented to the entire class.

Issue 2: Leveraging the Modeling Process

Reflection in Action. An exciting learning potential of modeling occurs at junctures during the model construction process when students pause and evaluate their current understanding using their model. At these points, students typically have developed hypotheses about the phenomena under study and attempt to verify these conjectures using their models. Given the nature of the inquiry cycle, reflection in action occurred casually throughout the model building process. For example, in the following dialogue taken from Barab, Squire, and Barnett (1999) we see students gaining an appreciation for the size of the solar system through their model building.

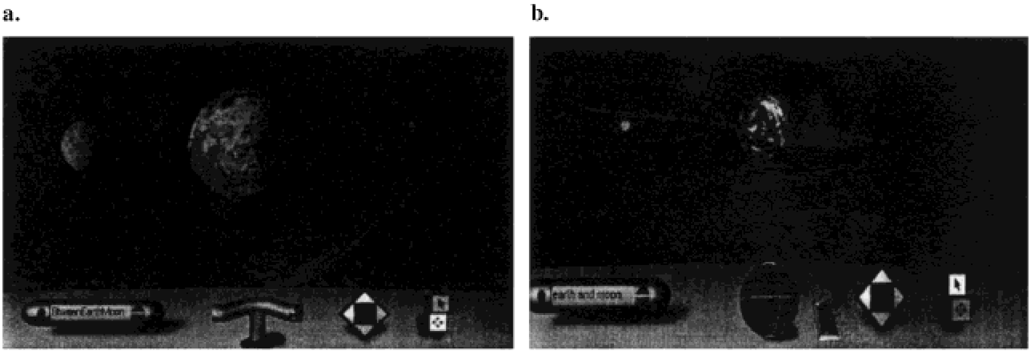

Figure 4. (a) On the left side we see the students' model demonstrating the orbital path of the moon and its phases. (b) On the right side we see the inclusion of the line of nodes to demonstrate when eclipses occur.

Terry: Are we going to be able to see all the planets?

Dave: No. Unless we're not proportionately correct with our distances. But that's OK. That's awesome right there [has all the planets in line]. I have everything set equal, size and differences, so I'm putting them in a line so you can see them.

Researcher: Yeah, but you're not quite sure if you can see them?

Dave: You can see it, can you see it? There's Mercury, there's Venus, earth's back there, if you can see it. That's what I wanted to check, figure if you could get them all in a line, like that.

Researcher: How far can you go?

Steve: The sun's a little bit bigger than everybody else. It's the big bully on the block.

Dave: It's pretty weird. Oh yeah, I want to set a viewpoint here [on sun].

Steve: Just think: the sun is an average star. Actually, it's a little bit small. Betelgeuse—in Orion—if we put Betelgeuse, in Orion, where the sun is right now, its radius would be all the way out to Jupiter's orbit.

Terry, &Ted: Wow!

Steve: Stars are big guys.

Ted: It all doesn't seem possible, does it? [After pausing for a moment to reflect, the students return to their modeling.]

In this case, the students view their model, inquiring about the sheer magnitude of the solar system and if they can faithfully represent the planets.

At other times, students' evolving models provide a forum through which rich conceptual discussions emerge surrounding astronomy concepts. For instance, understanding the motion of the sun across the sky is difficult for students to grasp because the sun's motion changes during the course of a year. In the following dialogue, taken from the summer 1998 VSS course, Taro and Todd discuss where the sun would be at its zenith (directly overhead) in their model (see Figure 5):

Todd: Ok, so [pointing to his model]. The sun will be at its zenith when it is at these four points [points to the locations where the solstices and equinoxes are in his model]

Taro: Almost, the sun will be a zenith anywhere along this line. [Taro, points to the ecliptic path in their model] See . . .

Todd: Ok, so when the sun is on that line, you will see the sun directly overhead all the time.

Taro: When you are standing right here [points to a location on the earth in their model]. Lets say that would be June 24th, then the sun is directly overhead there. If you are standing here [points to another location], say that is June 26th then the sun is directly overhead.

Todd: Ok, we are just going to have to move. I just don't understand.

Taro and Todd continue to discuss when and where the sun will be directly overhead in their model for the next few minutes, until the instructor joins the conversation below:

Instructor: So what if you were a little bit off the equator? The sun would have to go from here [points to the Tropic of Cancer in their model] to here [points to the Tropic of Capricorn in their model]. So imagine yourself standing in between the tropic and the equator.

Todd: Yes! So it falls in between the two geological features [the tropics]?

Instructor: Bingo! So if you are standing here [pointing to their model], how many times will the sun be overhead during the course of the year?

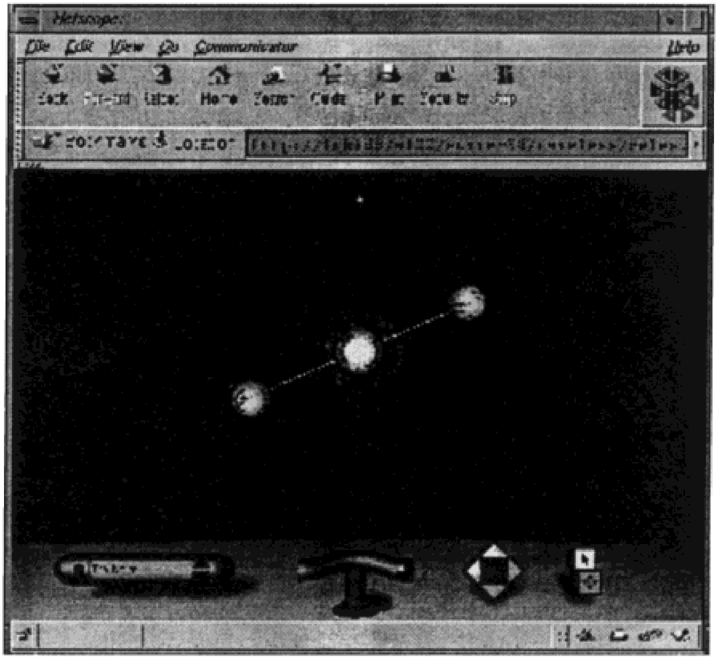

Figure 5. Todd and Taro's model of the Celestial Sphere, which they are using to try to determine when the sun will be directly overhead.

Todd: Two, right?

Instructor: Yes, because . . .

Todd: It goes in between the high point and low point twice. It goes between the two geographical points twice.

Taro: So if you are on a tropic how many times is the sun overhead?

Todd: Twice, right?

Taro: No, just once, because according this model [points to their model], the sun just goes up and down so it only hits the tropics once.

By engaging in the above discussion, Todd's understanding of how the sun travels across the sky during the course of a year is challenged by the motion of the sun Taro pointed out in their model. After further discussion, Todd comes to a robust understanding regarding the motion of the sun as shown in the following dialogue

Instructor: It [the sun] is like a yo-yo [points to their model]. It is a yo-yo around the ecliptic.

Todd: So it goes [moves his model around to gain a better perspective]. Ok, so from this view the sun only reaches that northern most point only once. So your question is how many times I will see the sun at the zenith at the tropic. I would only see it at the summer and winter solstices [points to his model to show the instructor what he means]

Instructor: So why do you get two at the other times?

Todd: Because the sun has to go between the two points. It goes down and back up.

By engaging in reflection activities during the modeling process, students critically examine their understanding, and through discussing their beliefs with team members and their instructor the sophistication of their understanding expands and becomes more aligned with scientifically accepted views of astronomical phenomenon.

Thought Experiments. 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 "thought experiments" in which student groups tackled enrichment questions posed by the course instructors (Brown et al., 1994). These questions typically involve changing their reference, changing the tilt or orbital speed of an object, or changing a planet's direction of rotation or revolution. For example, typical questions that student teams were asked were: "When you are on the moon does the earth have phases?" Or "How long is a day on the moon?" (see Table 3).

One example of a thought experiment occurred around the earth–moon–sun system in which students were asked by the instructor: "If you walked outside at night and could see a neon flag on the moon, how many days of the month would you be able to see it?" In this experiment, students use their understanding of the moon's synchronous rotation with respect to the earth and use their model to answer the question. In general, most students initially either are unsure or unable to articulate a response as is demonstrated in Todd's answer when asked about the length of the day on the moon during his spring term pre-interview below:

Interviewer: How long is a day on the moon?

Todd: The earth's day is 24 hours due to the rotation. I want to say 24 hours because of the relativity. Because it is relative to the earth. It seems to me that they go around one another, when one goes around the other does something.

To guide the students in resolving this question the instructor suggests that a flag be added to the near side of the moon in the model and observe the results. At this point in the model construction process, the CAVE became a valuable tool in aiding Todd and his group in visualizing the motion of the moon as it orbits the earth. Using the CAVE, the students were able to explore and directly experience how often the earth would rise from the moon, as well as how often the sun would rise on the moon. By viewing these dynamics in the CAVE, students developed an appreciation that the moon's synchronous rotation simply means that the same side of the moon always faces the earth and the earth will never rise or set when viewed from the moon. Below is the dialogue of a group and the instructor as they try to formulate a resolution to the above thought question in the CAVE:

Todd: What I don't understand is where the time comes in on this. Oh I guess as the moon goes through its phases you can see bits and pieces of the flag. Depending on, well, let's see, Ah now let's see, dark side, bright side, . . .

Comment: (*the team then looks at the objects in the CAVE for 4 min*)

Taro: What if I say the rotational period of moon and orbital period of the moon are the same?

Todd: As the earth around the sun?

Taro: No, no, the orbital period, rotational period—the spinning period, and the orbital period of the moon are the same.

Todd: And the result of that is being able to see that same side of the moon so as it follows, as the moon rotates, and it pitches up, in orbit, it follows the same time frame or path as the orbital.

Taro: Yes.

Instructor: Any other questions? Did this help?

Todd: It helps a lot with only that one side facing us!

In the post-interviews Todd's understanding of the fact that only one side of the moon faces the earth is shown by his ability to articulate that the earth never sets when viewed from the near side of the moon.

Interviewer: Ok, how long is a day on the moon. A day is the time from sunrise to sunset to sunrise again. Analogous to that of a day on earth.

Todd: The moon moves around the earth the same time, it is not really diurnal, but the earth has its motion of 365 days around the sun. The moon's rotation is exactly the same as its revolution. Well, I guess that answers the question. So the earth never sets on the moon. It would be perpetual day. The earth never goes below the horizon.

The CAVE illuminated additional astronomical concepts in the student projects that were not easily visible on the desktop. For example, in trying to determine whether the earth has phases when viewed from the moon, one student team observed the phases of the earth in the CAVE. This was an unexpected observation as the students had observed their model on their desktop and concluded that the earth did not have phases. However, in the CAVE these students positioned themselves on the moon, and watched the earth pass through its phases. Once in this position the students noticed that the sun's position was the cause for the phases. Thus, the student team reasoned that the relative position of the sun, earth, and moon produced the phases of the earth when viewed from the moon. However, the CAVE which requires viewers to wear headsets, was not a useful collaboration tool for this project-based course in which students, not software designers, collaboratively constructed their VR worlds. As such, the CAVE became more useful as a "reflection on" activity that occurred after the work on the models was completed.

These thought experiments not only provided students the opportunity to modify their ideas and beliefs through experimentation, but also served as an outlet for conversations in which students articulated and clarified their understandings of the phenomenon they were attempting to model. In this manner, the thought experiments were used as part of the ongoing student activity, not simply as a reflection on activity. For example, the question of, "What would happen to the earth's seasons if the earth was not tilted at all?" posed great conceptual difficulties for almost all student teams. In the following interaction, the student team had finished placing their viewpoints in their Celestial Sphere model and could point out the astronomical positions of the solstices and the equinoxes. The team was satisfied that their model could satisfactorily address the seed questions and began to focus their efforts toward exploring the above thought question posed by the instructor. In the following dialogue from the summer 1998 term we observe the student team using their model as a conceptual tool to develop a response to the thought question:

Todd: I have another question. I am still a little confused concerning what would happen to the seasons if the earth is tilted at zero degrees. [Points to his model on his computer screen]. That would mean the solstices would be on the ecliptic? What would happen to the equinoxes?

Taro: There would not be any seasons. [Points to their model]. See the equinoxes are already at zero degrees tilt, but the solstices are at 23.5 degrees tilt because of the earth's tilt.

Roger: What is the question again? Not sure I understand.

Todd: If the earth was tilted at zero degrees there is only one season. [Pointing to his model again] See from the point of view of the solstices and equinoxes they always see the same . . . what is it . . . latitude? Right, they would always be over the equator so the sun would be at zenith all the time on the equator, right?

Taro: Yes!

Todd: I thought there would be two seasons if the earth was tilted at zero degrees, because spring would start with the vernal equinox and the fall would start with the autumnal equinox, but that was not correct. There really won't be any seasons.

As a result of this thought experiment, Todd came to recognize that his previous understanding of the role of the earth's tilt in regard to the seasons was incorrect. Further, this type of reflection frequently led students to re-examine and change the design of their models. While the thought experiments incorporated aspects of reflection-in and reflection-on-action, there were other activities that can more easily be characterized as reflection-on-action.

Reflection on Action. In addition to the students exploring and asking and being asked questions concerning their understanding during the model construction process, they also reflect on how and in what way the modeling process influenced their understanding of astronomy. Typically these reflections involved the students asking: "Does my model represent the real world?" "How does my model represent my current level of understanding?" "How did constructing a model help me learn astronomy?" The latter question is of particular interest because astronomical phenomena are often difficult for students to grasp, in part because of their abstract conceptual nature, but primarily because they require students to understand dynamic events that occur in 3-D space (Parker & Heywood, 1998).

Traditionally, instructors have used physical 3-D models or 3-D pictures from books to facilitate student understanding of astronomical relationships and concepts (i.e., a light and two spheres to demonstrate eclipses and phases). These types of representations and models have distinct limitations and advantages when compared to student construction of 3-D VRML models. One advantage of constructing VRML models is that students can easily change the parameters of the model and run the model to test their evolving understanding. In other words, physical models are useful for allowing students to appreciate the 3-D nature of the system under study, but do not allow students to explore the system with time as a variable. Similarly, 3-D VRML models allow students to set viewpoints that permit them to dynamically explore snapshots of their model. That is, by placing the viewpoint at different locations in their model students can jump from one location to another and explore astronomical events as they unfold. For example, in the following dialogue from the summer VSS course, Steve is being asked by a guest visitor to reflect on his astronomy understanding and how his work in constructing a 3-D VRML model has helped to facilitate his understanding by a visiting researcher:

Visitor: Do you think you are getting a good understanding of what is occurring in the solar system?

Steve: Yes, definitely. Tomorrow we are going to see our projects in the CAVE. Our project showed the phases of the earth from the moon, and the phases of the moon from the earth.

Visitor: What is your major?

Steve: Telecommunications and a business minor.
Visitor: Right.
Steve: So I have to take so many science classes. So I chose astronomy. I don't really have a good concept of what is going on up there. To be honest I was not all that excited because I thought I would have to be plowing through the book, you know memorizing the distances between planets. Plus, being able to get into these things 3-D and really look at them from different angles and positions has been really useful for helping me to understand what is going on.
Steve: Watching it happen in 3-D it is fuller learning than looking at the images in the flat textbook. ... I watch the moon go through all the phases from the earth. [Shows his team's model to the visitor] Here in the book [points to the book] you can only see the pictures of the different phases. Even when I am out there watching it I can only see a certain phase and not see it all happen. Here I can see the entire range of phases. Much better than theoretically reading about it.

As part of each project each student and each student team had to write a paper describing the features, limitations and strengths of their models. For example, in the following excerpt from a team paper during spring 1999 term, they reflect back on how their model compares and contrasts with the real solar system:

> Another discrepancy in our model has to do with eclipses. Our model accurately models how solar and lunar eclipses work, but due to VRML limitations and our size distortion, the results are not completely accurate. Because VRML does not cast good shadows, the moon does not go dark, go red, or even change color at all when it crosses into the earth's umbra. Due to our size distortion, there is also almost always at least a partial solar eclipse. Since the moon is so much bigger in our model and so much closer to earth, it almost always covers part of the sun. From the surface of the earth, the five-degree difference in the orbital plane of the moon and the earth is not enough for a moon ten times as large and four times closer to earth to move as far away from the sun in the sky. In the real world, solar eclipses are much more rare.

This reflection on how their model compares and contrasts with the real world enables students to begin to understand that models allow for the understanding of complex problems through simplification and idealization. Further, by recognizing that their model is a simplification and may not be a completely accurate representation of the real world they must explain the differences between the real world and their model if others are to accept the value of their model.

Issue 3: Knowledge Diffusion

Given that course activity occurred at individual, group, and public levels, knowledge diffusion became a central part of course dynamics. It is important to clarify that our use of the terms knowledge and diffusion is "not meant to imply that knowledge has material aspects that locate it in time and space or that there is something that diffuses in a material sense" (Roth, 1996, p. 181). Instead, what we mean by knowledge diffusion is our observation that increasing members of the class began to use a specific conceptual resource or engage in a specific practice or be able to communicate with our research team in a manner that suggested deeper conceptual understanding. In this section, we begin with a discussion of the group dynamics and of the classroom knowledge diffusion process, and then present our posttest interviews which suggest that by the end of the course students could engage in sophisticated astronomical talk.

Orbital Motion. A team consisting of three students, Tom, Leasy, and Kara, spent three class periods studying the astronomy concepts associated with the moon and its orbital motion. Starting on the third class period of Project 2, they begin to explore the implications of the moon's orbital motion. Tom began the class by expressing his confusion over the synchronous orbit concept that he had read in his textbook the night before. The team discussed the meaning of synchronous orbits until Leasy stated that she understood it and that it meant that the same side of the moon always faces the earth. Tom was unsure but suggested that once he could see it in their model he would probably understand it better. Kara, taking control of the mouse, showed Tom that the moon is spinning in their model but that its rate is the same as its revolutionary (orbital) period. The team decided they needed to put viewpoints on both the earth and the moon to show the moon's synchronous orbit. By adding objects on one side of the moon (e.g., a neon flag discussed above) and putting a viewpoint on the earth facing the object, the team could demonstrate that because of the synchronous rotation and orbit, the same side of the moon will always face the earth. Some teams will notice this phenomenon without the instructor sharing his example of the neon flag.

It is frequently at these teachable moments that the class instructor will step in with a Socratic question to push student understandings to a deeper level. In this case, the instructor referred back to one of the original seed questions, which asked, "How often does the sun rise on the moon?" Tom asked,

> If the same side of the moon faces the earth, then does that mean the earth never rises . . . , and if the earth never rises from the moon does that mean the sun never rises on the moon.

In response to these questions from Tom, Kara stated,

> . . . this side of the moon [Kara pointing to the computer screen] has no sunlight shining on it now but as the moon revolves and reaches its new phase . . . that side now sees the sun. So the sun must rise somewhere when the moon is at quarter phase. I think that is right. What do you think Leasy?

After Kara's explanation, Leasy and Tom were still confused, agreeing that: the moon's orbital period is the same as its rotational period, so the sun should not rise. Kara, again taking control of the mouse, showed Tom and Leasy that the moon is spinning (rotating) in their model, but that its revolutionary (orbital) period as part of the earth–moon system around the sun is not the same as its rotational period on its axis—like with the earth. Therefore, the sun (and not the earth) would rise if they were on the moon. At this point, the class was ending and the team set research tasks for each member to perform before the next class to help them to further understand what they had accomplished. The next class period, Tom broached the topic of the moon's rotation again, stating:

> I think we need to put viewpoints on both sides of the moon because if Kara is right, that should show how the sun rises on the moon. At least that is my understanding right now.

He continued to explain to the team that as the moon revolves around the earth, they should see the sun rise once during its orbit. They then proceeded with animating their model, and after observing that the new viewpoints supported their hypothesis, they congratulated each other.

Phases of the Moon and Eclipses. Leasy, pointing to their model, also recognized that they could see the phases of the moon and pointed out the positions of a full moon, quarter moon, and new moon. At this point, the instructor asked the students how often their model showed a solar eclipse. After observing their model, Kara and Leasy stated that they had forgotten to include the five-degree tilt of the moon because they were getting too many eclipses. Tom, confused again, wanted to know, "What is the moon's tilt relative to? And why is it important?" Leasy explained to Tom that the moon's orbital plane is tilted relative to the ecliptic. She then performed the tilt in their model. Kara, using the model as a reference, pointed out to Tom that when the moon is above the ecliptic plane there will not be an eclipse. This is because the earth, moon, and sun are not lined up. Unfortunately, class was ending; however the instructor suggested that the students research the line of nodes.

The next class period began with the team comparing their model to the real solar system. Once the students were satisfied their model was working, they began the task of including the line of nodes. All the team members read about the line of nodes, but no one was sure that they completely understood it. In a team first discussion of the nature of the line of nodes, Leasy stated that it was the line formed from the intersection of the moon's orbital plane and the ecliptic. Tom, beginning to understand the importance of the lunar orbital tilt, commented:

> That is why the five-degree tilt of the moon's plane was so important, because if it was not there then the line of nodes would not exist, and we would have eclipses all the time.

Leasy noted that the line of nodes is not a permanent line in space but rotates as the earth and moon the orbit the room. Extending this discussion, Kara suggested that they try to show the line of nodes by placing a line in their model. Together, the team placed a line in their model to represent the line of nodes. With this line in the model, it became a straightforward process to decide when eclipses would and would not occur—when the earth, moon and sun crosses the line of nodes at the same time.

Inter-Group Knowledge Diffusion. In addition to the shared construction of knowledge within groups, we also have much inter-group knowledge diffusion. This occurs formally through the development of compare–contrast papers, and inter-group presentations. However, there is also inter-group knowledge diffusion that was not stimulated by the mandated class structures. Frequently, the catalyst for knowledge diffusion is the problems that arise during the construction of the models or addressing the questions. For example, when a particular team is struggling with either a technical (how to create an orbit) or an astronomy-oriented problem (what is the moon's orbital tilt), the instructor or another student informs the struggling student team that another team has solved it, or is working on the same problem, and that it would be beneficial to engage in a conversation with that team.

One example of knowledge diffusion occurred in the earth–moon–sun project when one student overheard another group talking about their line of nodes (Barab, Hay, & Yamagata-Lynch, in press). In this scenario, Erica developed an earth–moon–sun model that included a visualization of the line of nodes. We pick up the interaction as a student from another group (Todd), comes over to Erica's group for help.

> Todd: There is a rumor that you're working on the line of nodes in your model. I'm not sure what it is.
>
> Erica: It's where the plane of the ecliptic between the sun and earth and the plane of the earth and the moon intersects. ... It is not a real line... Whenever the moon crosses this line [pointing to the screen] there is an eclipse... [*Todd nods*].
>
> Erica: [*pointing to the screen, Erin continues*] The way I made mine, I made a long cylinder and made it a very long line.

Todd: Wow, that thing is a cylinder!
Erica: Yeah, (*pointing to a line on the screen*) . . . I grouped the earth and the line of nodes so the line of nodes would stay with the earth when it revolves.
Todd: That's a good idea. So what you are trying to demonstrate here is when the line of nodes come together . . . That's when the eclipse happens . . . . That's good- . . . Wow!
Erica: Yeah this is going to be neat . . . When I did it last time I grouped it wrong so be careful.
Todd: Thanks!

Todd then returned to his group where he explained to his group members the concept of the line of nodes. Two days later, they, with some help from Erica, successfully added the line of nodes to their model.

Some students appreciated the opportunity to engage in collaborations and used these to evolve their own models—as evident in the below interview.

> While we were doing our project, we noticed that the other groups were adding the line of nodes to their project. We decided that we should also add these to show where eclipses occur. We added the earth's ecliptic and the moon's orbit as big, round, and compressed transparent spheres. Then, where the ecliptic and the orbit crossed is where we put the line of nodes.

However, other more competitive students described cross-group collaboration to be inappropriate—as evident in one following student's reflection paper.

> As far as comparing our model to those of the other groups, why bother? One part of the assignment three description reads, "Talk with the other teams. Other teams have already figured out much of what you will have to do, so take advantage of their work and share your work with them." I interpreted that as meaning "leech off of the Orange Team" [referring to this student's group name]. Though I may not have shown it, I was totally shocked and pissed off when you told that other student to rip off my frames. Additionally, you had Ralph explain his awesome core-view to other members of the class. What's the point of excelling, if the professor is going to encourage other students to plagiarize our work? I don't know if the other members of my group feel as strongly about this as I do, but I refuse to help any of the other students outside my group with anything, under current course politics.

This was clearly not the expressed norm, and over the sequence of courses we only had a couple of students express such heartfelt disdain for group work. However, this feedback has led us to currently spending more up-front course time explaining why we do group work and why we encourage cross-group collaboration—in a very real sense, sharing our pedagogical commitments.

Student Learning Outcomes. In addition to examining the process of learning that occurs during the model building and testing process we are also interested in the ability of students to articulate and explain their understanding of astronomy. Students in the first two iterations of the course took the traditional Introduction to Astronomy, multiple-choice final examination and averaged in the low 90s, which is as good or better than average scores in the lecture-based courses. (interview with course instructor, May 12, 1998). This was exciting given that there were no explicit instructor preparation or lectures with respect to these multiple-choice questions (given it was only 5% of the overall class grade), and answering multiple-choice type questions was not consistent with the other practices of the course (building models).

More important, from our perspective, was that pre–post interviews suggested that students developed deep understandings of astronomy concepts (Keating, et al., 1999). The pre-interviews, not surprisingly, revealed that many students held the same alternative conceptions concerning the seasons, eclipses, and phases of the moon as reported in Comins (1993). Only one student articulated a satisfactory explanation of the difference between a full moon and a lunar eclipse as having to do with the tilt of the moon's orbital plane. Todd, a student with minimal science background, demonstrated his confusion with the cause of lunar eclipses in the following sequence:

> Interviewer: When do we get a lunar eclipse?
>
> Todd: I think it has something to do with the day night sequence. I guess that when the Earth is turning, we see different sides of the moon.

The post-interviews revealed that the students had altered their prior conceptual understandings of astronomy, developing cogent explanations for many difficult astronomical phenomena. For instance, when the students were asked to change their frame of reference as in the case of the thought experiments, students' conceptual knowledge scores increased significantly from the pre-interview to the post-interview, as they did when averaging across all questions. Further, the students understood, on a qualitative level, concepts that are rarely covered in beginning astronomy courses, such as line of nodes. Returning again to Todd as an example, in his post-interview statement Todd utilized two conceptual tools developed during the VR modeling process, the five-degree tilt of the moon's orbital plane and the line of nodes, to explain the reason for lunar eclipses.

> Todd: The moon is going around the earth and the moon is behind the earth and the earth is going around the sun. The ecliptic and the rotational path intercept at the line of nodes and due to the 5-degree tilt they cross at certain points. If it is a total eclipse that is it is an umbral eclipse it is beet-red, if it is penumbral eclipse then it is partial eclipse. It depends on when the moon is on the line of nodes.

Todd arrived at a rich conceptual understanding of lunar eclipses. In a similar fashion, by the end of the course, seven of the eight students utilized the concepts of the moon's orbital tilt and the line of nodes to explain the earth–moon–sun system. The active engagement of the students in modeling the system in three dimensions appeared to have confronted the often-overlooked phenomena of the moon's orbital tilt. Furthermore, the concept of the line of nodes became a central component of all the models. Beyond understanding how the phases of the moon behave, students also described what the phases of the earth would look like from the moon or any other planet. This ability to transfer the phases concept from one situation to another implies that the students had a deep understanding of the ideas involved.

More generally, Keating, Barnett, and Barab (1999) reported the following findings when comparing students in the VSS course with students in the traditional introduction to astronomy course. First, all students that participated in the VR course experienced significant gains in their astronomy conceptual knowledge. Further, they concluded that, "The VR modeling environment seemed to be particularly effective in supporting student learning in two fundamental ways: (1) Allowing students to change frames of reference, and (2) Supporting students' ability to visualize abstract concepts." This ability to change viewpoints and quickly shift perspective from one side of the earth to the moon or to Jupiter appeared to facilitate the development of robust conceptual understandings regarding perspective taking—a fundamental concept and activity in astronomy. Complementary to the ability to change frames of reference, the modeling environment also supported the students' ability to visualize abstract concepts, with students repeatedly referring to "their models" in the post-interviews. These findings more generally provide preliminary evidence of the power of this course.

In addition to these desired learning outcomes, there are particular aspects of the VSS learning environment that were more problematic and may have been impediments to student understanding. Across semesters we noticed that there was a tension between students developing 3-D models that represent, demonstrate, or explain some astronomical phenomenon, and the students constructing a compromised (simplified) model that appeared aesthetically pleasing. For example, the third project involved constructing a model that was accurate in scale. However, when students constructed their model to scale, they were uncomfortable with the results because the model, though accurate, was difficult to see and explore on their desktops. Therefore, students frequently either compromised the astronomical accuracy of their original model or developed one model that focused on specific salient conceptual features for class presentations and one that was more conceptually accurate. One interesting finding was that in spite of students articulating this discrepancy between their models and actual scale, post-test interviews revealed that many students had limited appreciation for the scale of the solar system (Keating et al., 1999). We are currently exploring possible interventions to address this unexpected course limitation.

Conclusions

The VSS course was designed to engage students in constructing concrete artifacts and, in the process, develop rich understandings of astronomical phenomena. A central feature of this course has been the use of virtual reality as a construction tool, providing students with direct experience with objects and dynamics (interacting astronomical objects) not otherwise possible because of the nature of the real objects. Predicated on a participatory pedagogical framework, it was not our intention to immerse students in virtual worlds that we developed, but to establish a context that supported them in directing the learning/modeling process and allowed them to learn from their model. More specifically, we found a project-based framework in which student work was organized around a shared artifact to provide a useful pedagogical model for learning astronomy.

Our conception of a project-based framework does not simply entail having students working collaboratively in groups. The types of participant structures that were developed include those that support individual activity, local activity, and public activity (Hall & Rubin, 1998). With respect to local (group) activity, students spent much of their in-class time working collaboratively either in parallel or sharing the same computer. The use of the internet allowed students to share each other's work in a manner that also made their work public. With respect to public activity, student teams shared their work with other classmates through internet, in the CAVE, and during class presentations. These public displays of group work provided an important motivator for in-class work. Throughout the project building and as part of student reflections, they also engaged in private activity. We believe that project-based work must create participant structures for all three types of overlapping activity (private, local, and public), and it is the interrelations of all three that provide motivation for and meaning to the others.

Moving from a lecture-based to a project-based focus is not a straightforward process. The course structure, in spite of our initial planning, has passed through many ebbs and flows. In support of this evolution, we have engineered our course development and research as a series of design experiments with the intention of developing various curricular constraints, tracing the resultant learning, and cycling these findings back into the next iteration of the course (Brown, 1992). Issues that have been central in the course evolution include the role of the teacher, supporting the collaborative process, facilitating inquiry through three levels of questions (seed questions, base questions, and enrichment questions), learning through modeling, and supporting knowledge diffusion.

We have found that regardless of our curriculum modifications and the power of the technology, the teacher remains an essential central component in our learning environments. However, in the participatory learning environments that we have been developing, the teacher's role is reconfigured from didactic caretaker and gatekeeper of knowledge to facilitator of the knowledge construction process, directing students down profitable paths, modeling an engaged mind, problem-solving with students, posing questions, and providing a rich context with needed resources (Barab, Squire, & Barnett, 1999). Most interactions between the instructors and the students were Socratic in nature and centered on the students' model or the modeling process. If the students were unable to answer a question by manipulating their model, the instructors would ask the students what needed to be added to their model to answer the question. This questioning allowed students (and instructors) to determine gaps, helping students identify modeling and conceptual limitations without depriving them of ownership over the learning process.

When researchers adopt a distributed cognition view of learning, the components of the learning environment as well as the communication and sharing among individuals become focal points for the diffusion of knowledge (Pea, 1993). However, for this diffusion to occur, it has to be represented externally in the form of inscriptions, shared artifacts, or discourse (Bell & Winn, 2000). In constructing models, our VSS students engage in a process where their understanding of astronomy is distributed across their model, a graphical inscription, which becomes a tool to examine, and is apart of, their understanding of astronomical events. For example, our interviews suggest that when students first begin the construction of a model, they typically have their own mental model of what the final product should look like. However, by gathering information from their textbook and through discussions with their peers and interactions with the instructor, new distributed meanings are developed and evolved.

These meanings can then be examined and tested by using the tools available to the members of the community, in this case 3-D modeling software. These experiences facilitate discourse, question-posing, and hypothesis formation by allowing students to construct and manipulate a visual representation of their shared understanding that all members can access. This visual representation and the discourse is not static but is fluid and open to question as each student brings to bear their individual knowledge and attempts to integrate it with the shared understanding embedded in their current construction. As additional information is reconstituted and coupled with the affordances of the modeling software (placing of viewpoints in this case), the model undergoes refinement through which its fluid properties, and in the process students' understanding are continually being transformed into coherent descriptions of the natural world.

Consistent with the CSIC pedagogical framework (Hay & Barab, 1999), we have described the practice of modeling as occurring in two overlapping and recursive stages, an enactment stage and a visualization stage. Students start by collecting resources and planning the model they will build. Following the collection of resources and planning, they begin the construction of their virtual models, enacting facts and concepts about the earth, moon, and sun. Once the virtual model is built, students then pose questions of the model, initially seeded from the instruction and then added by the students themselves. During the visualization stage, students develop rich insights into into astronomical phenomena. For example, to answer questions about an eclipse, many students decided to construct two semi-transparent disks to visualize the intersection of the moon's orbital plane and the plane of the ecliptic—the line of nodes. The concept of line of nodes is often left out of introductory astronomy courses because the dynamic, 3-D nature of the concept is so difficult for students to understand at a meaningful level.

With respect to learning astronomy, it was our initial contention that astronomy education has an opportunity to make a profound shift from an emphasis on delivering content through large lecture classes to one in which students construct concrete artifacts representing the dynamics of the solar system and, in the process, learn astronomy. We have found this model to be an effective intervention that has supported students in developing deep understandings about various astronomical phenomena. The concrete instantiation of students' understandings that are distributed across VR artifacts supports the development of grounded understandings, not as separate concepts stored in the modeler's brain, but as distributed descriptions that were situated across and through their experiences (Pea, 1993). Through this process, concepts (plane of the ecliptic, relative scale, mathematical formulas, line of nodes) become living phenomena that are *actualized* and not simply *realized* (Barab, Hay, & Duffy, 1998).

Implications

In this article we have described a course predicated on our goal of designing technology-rich, inquiry-based, participatory, learning environments for supporting students in learning astronomy. Our findings indicate that this initial course was a successful innovation in which the learning of astronomy occurred through the construction of VR models. One of the exciting features of virtual reality is its potential for immersing the learner in various contexts that would not be possible through other means or for visualizing information (the temperatures of a frontal system). Developing effective approaches based on actual experience (and not theoretical conjectures) is essential if we are going to develop environments that leverage the potential of these technologies to impact learning. It is for this reason that we have found Brown's (1992) notion of the design experiment to provide such an useful design approach.

Although there is a growing theoretical base to design these types of courses, it is imperative that researchers also establish an empirical base to ground this perspective, examining learning that is actually occurring in these contexts. With this goal in mind, we design entire courses and interventions introduced as curricular constraints that establish learning opportunities for our students. As we continue to do research and analyze the data we intend to develop grounded theory with respect to the potential of our pedagogical committments for facilitating learners in becoming knowledgeably skillful (Glaser & Strauss, 1967; Strauss & Corbin, 1990). Design experement like grounded theory development, in which the data and the theory continually (re)define each other, "keeps a particular framework from becoming the container into which the data must be poured" (Lather, 1986, p. 267). It is our commitment to develop a pedagogical model that is constantly tested against the empirical evidence to refine our thinking, providing our colleagues with explanatory models about learning and instruction that are consistent with empirical data and, as a result, are of pedagogical value. For this paper, our goal was more modest, providing an overall description and sharing a few examples that indicate the potential of our participatory learning environment for supporting student understanding of astronomy.

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