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ARTICLES

Using Activity Theory to Understand the Systemic Tensions Characterizing a Technology-Rich Introductory Astronomy Course

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In this report of our research on a computer-based three-dimensional (3-D) modeling course for learning astronomy, we use the central tenets of activity theory to analyze participation by undergraduate students and instructors, illuminating the instances of activity that characterized course dynamics. Specifically, we focus on the relations of participant (student) and object (3-D models and astronomy understandings) and how, in our course, object transformations leading to scientific understandings are mediated by tools (both technological and human), the overall classroom microculture (emergent norms), division of labor (group dynamics and student–instructor roles), and rules (informal, formal, and technical). Through analysis of the data, we interpreted and then focused on two systemic tensions

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as illuminative of classroom activity. With respect to the first systemic tension, we examined the interplay between learning astronomy and building 3-D models. Results suggested that instead of detracting from the emergence of an activity system that supported learning astronomy, model-building actions frequently coevolved with (were the same as) astronomy-learning actions. With respect to the second tension, we examined the interplay between prespecified, teacher-directed instruction versus emergent, student-directed learning. Our results indicated that it was rarely teacher-imposed nor student-initiated constraints that directed learning; rather, rules, norms, and divisions of labor arose from the requirements of building and sharing 3-D models.

INTRODUCTION

Moving away from teacher-centered or lecture-based environments, we have been developing participatory learning environments that are technology rich and allow students to ground their understandings within their own concrete experiences (Barab, Hay, & Duffy, 1998). These environments take advantage of emerging technologies to establish participatory learning environments that immerse students within contexts that challenge, ground, and, ultimately, extend their understandings. The emphasis of participatory learning environments is the learners' emergent practices in relation to the need at hand. Predicated on a social constructivist philosophy, the role of teacher switches from one of telling students correct answers to guiding student activity, as they direct their own learning process (Bednar, Cunningham, Duffy, & Perry, 1992; Dewey, 1963; Edwards, 1995; Vygotsky, 1978).

Consistent with Papert's (1991) constructionist pedagogical framework, participatory learning environments support learners' building understandings through the collaborative construction of an artifact or shareable product. These environments are frequently collaborative in nature, with students negotiating goals, tasks, practices, and meanings with peers (Blumenfeld, Marx, Soloway, & Krajcik, 1996; Land & Hannafin, 1996; Nastasi & Clements, 1991; Savery & Duffy, 1996). Rather than presenting instructional treatments, the goal is to establish rich environments that encourage explanation and discovery, nurture reflection, and support students in carrying out practices that embody personally meaningful and conceptually functional representations (Barab et al., 1998; Hannafin, Hall, Land, & Hill, 1994; Jonassen, 1991). Said another way, these environments are intended to support the emergence of activity systems that allow learners to extend their understandings.

In general, technological advancements have made possible many new exciting learning opportunities, supporting students in collaborative learning and inquiry (Barab, Squire, & Dueber, 2000; CTGV, 1993; Edwards, 1995; Jonassen, 1996; Koschmann, 1996; Scardamalia & Bereiter, 1994; Winn, 1995). In particular, Barab and colleagues (Barab, Hay, Squire et al., 2000; Barab, Hay, Barnett, & Keating, 2000; Barnett, Barab, & Hay, 2001) have been researching students using generic 3-D-modeling construction tools to build model solar systems and conceptual understandings of astronomical phenomena. From a learning perspective, the act of modeling allows students to engage in a design process, beginning with a set of tentatively accepted theories and evolving into coherent understandings as represented in their models (Dede, Salzman, Loftin, & Sprague, in press; Jackson, Stratford, Krajcik, & Solloway, 1994; Lehrer, Horvath, & Schauble, 1994; Roth, 1996, 1998; Sabelli, 1994; Stratford, Krajcik, & Soloway, 1998). While constructing models, a "conversation" unfolds through which interactions occur among students, among students and the teacher, and among students and their models and the materials (inscriptions) of their work, as students attempt to create meaning through and from their constructions (Roth, 1996). Through participation in this process students 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 (Barab et al., 2001; Roth, 1998).

In this article, we discuss the implications of our research on technology-rich, participatory learning environments for engaging undergraduate learners in constructing understandings about scientific phenomena. In discussing the implications of this research and to better understand the potential of our work, we conceptualize course findings using the theoretical framework of activity theory (Engeström, 1987, 1993; Leont'ev, 1974, 1981, 1989; Nardi, 1996). More specifically, in this report of our research we use the central tenets of activity theory to analyze participation by students and instructors, illuminating the nested instances of activity that characterized course dynamics. In describing the course dynamics, we show the historical development and multiple iterations that our course passes through. In describing these dynamics, it was not our intention to "black box" the activity system, simply presenting one metacharacterization as representative of all course actions. Rather, in an attempt to capture the dynamic unfolding of course participation we present multiple snapshots and build multiple explanations of course actions at different time periods—highlighting the course-in-the-making instead of simply the ready-made course (Latour, 1987). Given that activity systems are characterized by systemic tensions, the data reporting and analysis is framed around the pervasive tensions that were identified as central to the course dynamics.

ACTIVITY THEORY

Activity theory is a psychological and multidisciplinary theory with a naturalistic emphasis that offers a framework for describing activity and provides a set of perspectives on practice that interlink individual and social levels (Engeström, 1987, 1993; Leont'ev, 1974; Nardi, 1996). Although new to Western researchers, activity theory has a long tradition as a theoretical perspective in the former Soviet Union (Leont'ev, 1974, 1981, 1989; Vygotsky, 1978). When discussing activity, activity theorists are not simply concerned with "doing" as a disembodied action but are referring to "doing in order to transform something," with the focus on the contextualized activity of the system as a whole (Engeström, 1987, 1993; Kuutti, 1996). The "minimal meaningful context" for understanding human actions is the activity system, which includes the actor (participant) or actors (subgroups) whose agency is chosen as the point of view in the analysis and the acted on (object) as well as the dynamic relations among both.

These relations between participant and object are not direct; rather, they are mediated by various factors, including tools, community, rules, and division of labor. Figure 1 portrays a pictorial representation of a generic activity system as conceptualized by Engeström (1987, 1993). We are referring to participants as the individuals or groups whose agency is selected as the point of view for the analysis. Objects can be raw materials, conceptual understandings, or even problem spaces, "at which the activity is directed and which is molded or transformed into *outcomes* with the help of physical and symbolic, external and internal tools" (Engeström, 1993, p. 67, italics in the original). The community of a system refers to those individuals, groups, or both who share the same general objects, and are defined by their division of labor and shared norms and expecta-

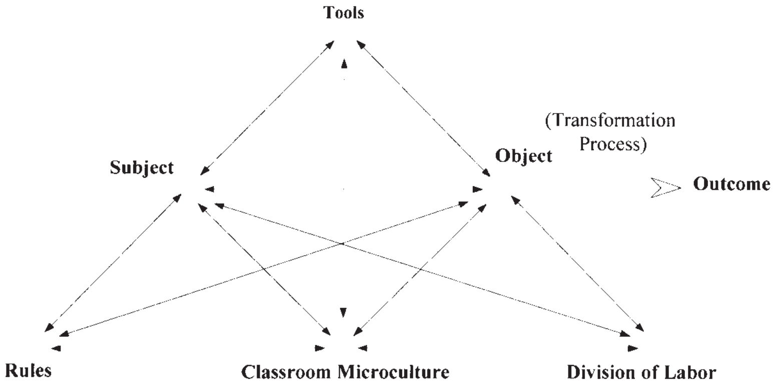

FIGURE 1 The basic structure of human activity. The figure illustrates the mediated relationship between participant and object, and the interrelations among the various components of the system.

tions. Specifically, divisions of labor can run horizontally as tasks are spread across members of the community with equal status, and vertically as tasks are distributed up and down divisions of power. Last, activity systems are somewhat constrained by the formal (systematic, general, and expected), informal (idiosyncratic adaptation), and technical (mandated and, potentially, written) rules, norms, and conventions of the community.

The components of activity systems are not static components existing in isolation from each other but are dynamic and continuously interact with the other components through which they define the activity system as a whole. From an activity theory perspective, an examination of any phenomenon (e.g., learning in the classroom) must consider the dynamics among all these components. In addition to the interactions of an activity system of a particular time and space, it is important to note that an activity system is made up of nested activities and actions all of which could be conceived of as separate activity systems or other instances of the same system depending on one’s perspective. For example, although the computer may serve as a tool in a current action, at an earlier time this computer may have been an object or an outcome in what may be conceived as a previous action of the same activity system or even as a different activity system. In a similar fashion, technical rules that affect a current activity system (e.g., lesson plan) could be the outcome of previous actions through which the technical rules were created.

A focus of activity theory is on how participants transform objects, and how the various system components mediate this transformation. With respect to the role of computers, for example, activity theorists are concerned with how these tools mediate the relations between participant and object. Therefore, it is not simply the human–computer (participant–tool) interaction that is fundamental to understand, but the participant–object interactions as mediated by the computer that become crucial (Kuutti, 1996). This perspective expands the unit of analysis from the mind of the individual (as in traditional cognitive research) or from the human–computer interaction (as in traditional human–computer interaction research, Carroll, 1987, 1991), to the entire activity system (Barab, 2002).

Activity systems are characterized by their internal contradictions (Engeström, 1987, 1993; Leont'ev, 1974). These contradictions are best understood as tensions among the components of the activity system. For example, in school learning there is a pervasive tension between learning the material to receive a grade (what Lave, 1993, described as the "exchange value" of what is learned) and learning material because of its importance in addressing real-world problems (what Lave described as the "use value"). Tensions are critical to understanding what motivates particular actions and in understanding the evolution of a system more generally. These tensions can be thought of as system dualities, and it is through understanding the interplay within and among these dualities that one can best understand and support the continued innovation of the system. Wenger (1998) argued that it is the interplay within the dualities that drive the system, with the design goal being to leverage the dynamics of system dualities and not to treat them as polar opposites or to eliminate one side or the other. As tensions enter the system they become the moving force behind disturbances and innovations and eventually drive the system to change and develop.

In summary, we view activity theory as providing a nondualist theory for describing the inseparability of learning and doing. In contrast to traditional theories that suggest learning is a precursor to activity or, the reciprocal, activity (sensory, mental, and physical) is a precursor to learning, activity theory avoids these dualisms by conceptualizing learning as practice and practice as learning (Engeström, 1999). As such, distinctions between practice and understanding or between individual and "context" also become trivial (Barab & Duffy, 2000). Similar to Rorty's (1979) *epistemological behaviorism* and Dewey's (1925/1981) *pragmatic social behaviorism*, the perspective being advanced is postpositivist in that it rejects theory–fact and fact–value dualisms, and is nonreductionist in that it conceives practice (activity) as part of a system (Barab et al., 1999; Garrison, 1995). From this perspective, context is not simply a container nor a situationally created experiential space but is an entire activity system, integrating the participant, the object, the tools (and even communities and their rules and divisions of labor) into a unified whole (Engeström, 1993). As stated earlier, it is the sum of these components and the tensions among them that influence the types of transformations a participant can have on an object. An examination of a course must address all these components, as well as the inherent tensions, as a unified system. It is with these goals in mind that we turn to a discussion of the methodology used for the study.

THIS STUDY

The VSS Course

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 CosmoWorlds, a virtual reality modeling language editor (VRML), 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 on one or two computers. The curriculum was developed collaboratively by an astronomy professor, two educational psychologists, and a graduate student studying astrophysics and instructional systems technology.

The current evolution of the course requires students to build three projects with the expectation that they will model various astronomical phenomena on their computers. These are outlined in detail in the course syllabus, passed out on the first day (see Table 1). 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 instructor-developed seed 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 be addressed. Each group negotiates plans to answer the questions, identifies resources (textbook, world wide web, 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 these instructor-supplied seed questions, students are also 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 modeling process, over the period of project development.

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 instructor’s seed questions that are given to all students before the model constructing process begins, base questions are presented to groups when they are ready, at the discretion of the instructor. Last, we have also developed a series of “enrichment” questions, in which students are expected to pose “what-if” questions to their models, probing and challenging the depth of understandings. Unlike the seed and base questions, these questions are not introduced to each group but are available to the instructor for groups that he perceives as capable of addressing, and potentially benefiting from, more advanced questions.

Each project has four concluding tasks. First, teams create a joint paper describing the features of their model. Second, individual students present and explain his or her team’s model to students

TABLE 1
Course Project Descriptions

Project 1	Project 1 is to model the Celestial Sphere. This project requires students to model fundamental astronomical concepts concerning the equinoxes, solstices, and ecliptic and celestial equators. Students decide on 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 2 is to model 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.
Project 3	Project 3 is to model the entire solar system, comparing and contrasting both the terrestrial planets and Jovian planets. Specifically, students are expected to make a model of the Sun, eight planets (Pluto and Ceres as options), six satellites (Moon, Galilean satellites of Jupiter, Titan, and Triton), the Saturn ring system, and with the option of adding comets and asteroids. Again, these bodies must have their proper orbits, sizes, colors, spin, tilt, distances, and interior structures.

from other groups, occasionally using the immersive 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.

Curricular evolution. We have engineered our research and development as a series of "design experiments" (Brown, 1992), with the intention of carrying out multiple layers of analysis. This process involves introducing various design modules (thought experiments, stand-and-deliver sessions, compare–contrast sessions, modeling challenges) in our courses, and "tracing" the emergence, evolution, and diffusion of practices, understandings, perceived constraints, and artifacts as they relate to each module. Findings related to these various levels of analysis are then fed back into classroom design, and we continue to examine how these innovations affect the learning process. Though the basic tenets of the curriculum have remained the same since the course prototype, our series of design experiments has led to numerous curricular revisions (Barab, Hay, Barnet, & Keating, 2000). For example, in the VSS prototype, students were provided a description of model expectations and a list of questions from which the final exam would be derived. The model description and the examination questions, in essence, provided structure for the students but relieved them of formulating good research questions to explore through their models and limited the inquiry process.

In the current course framework, we have abandoned the explicit description of what the first model must include. Instead, the instructor uses seed, base, and enrichment questions in the manner discussed previously to support students in developing their own model constraints. This curricular evolution, based on the results of our initial design experiments, resulted in exciting outcomes. First, it changed the professor's ability to answer the question, "How good do I have to make the model?" In the prototype course, it was a rather arbitrary judgment based on the professor's assessment of what the students could do in the given time frame. In the current courses, the answer is, "Good enough to answer the question(s)," thus, turning the question into an opportunity to further encourage the inquiry process. Second, 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. Thus, students are now being guided to engage in the scientific inquiry process of problem posing, formulating, solving, and reflecting through the construction of their astronomical models.

Another important evolution relates to the challenges of learning the astronomy, while at the same time also learning the technology. It is our intention to contextualize the learning of the technology around the building of student models. As such, we did not want to take the first week teaching the technology, and then begin introducing astronomy at week two. However, in the spring semester, Project No. 1 immediately immersed the students in modeling the complex orbital dynamics of the Earth–Moon–Sun system as they were learning the technology. As such, students were overwhelmed, for example, trying to place "viewpoints" in their model (cameras allowing the viewer to experience the VR world from various perspectives and locations) when the object they wanted to move would be constantly changing its location in three-dimensional space. To address this problem, 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. Then, 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, Barnett, & Keating, 2000; Barab, Hay, Squire, et al., 2000).

General Research Agenda

In general, our research can best be described as naturalistic inquiry, with grounded interpretations based on both quantitative and qualitative data (Guba & Lincoln, 1983; Scriven, 1983; Stake, 1983). 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 and group meetings and 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.

For the initial pilot (8 men, 6 women) and the first two semesters of the course (Spring 1998, 8 men, 2 women; Summer 1998, 6 men, 3 women), we had one researcher and an accompanying video camera assigned to each group of students (four groups of two, four groups of three, and two groups of four, respectively). 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 semistructured interviews with students and teachers two to three times in each iteration of the course, and, after the completion of the course, we conducted structured interviews probing student understandings. These data collection efforts resulted in a large corpus of the data, including three 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 online databases containing approximately 3,500 “episodes” of coded activity (Barab, Hay, & Yamagata-Lynch, 2001). 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.

Pre–post interviews.

Pre–post interview data was used not as a separate evaluation of the activity system, but as part of the interpretation of the outcome of the activity system (see Figure 1). To clarify, when we use the term *outcome* we are not referring to a separate entity somehow distinct or resulting from the system. The outcome is an integral part of the system, just as are tools or division of labor. The interview questions were semistructured, 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 (Comins, 1993; Schoon, 1993; Sneider & Ohadi, 1998), and from consultation with faculty members from the Astronomy Department at Indiana University. Most relevant to this study were the following two questions: (a) Compare and contrast the differences and similarities between a Full Moon and a Lunar Eclipse, and (b) What causes the seasons of the Earth?

The fifteen 30-min preinterviews 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 whiteboard for drawing to demonstrate their explanations. The interviewer asked probing questions to establish the depth of students' conceptual understanding. The postinterviews were conducted during the last week of the course, and typically lasted 30 min to 60 min. Again, the students were asked to verbally express their understandings and were encouraged to manipulate spheres or draw on the available whiteboard.

Activity theory as an analytical tool. Using activity theory as our theoretical lens and analytical tool, we examined the relations of participant and object as mediated by the primary components that constitute an activity system: (a) tools (both technological and human), (b) the overall classroom microculture (emergent norms), (c) division of labor (group dynamics and student–instructor roles), and (d) rules (informal, formal, and technical). Engeström's (1987) triangle is used to define the component structure of each of these instances of activity.[1] Leont'ev (1974, 1981) distinguished between actions and activities, with activities being longer-term formations of chains and networks composed of individual and cooperative actions. Activities are realized through actions; however, actions cannot be understood without a frame of reference to the larger activity system—that is, without reference to the larger context through which these actions are realized.

In this study, we examined actions (or sequences of actions), and framed these in terms of the mediating components that constitute an activity system. Although the boundaries we chose to frame an action (or a series of actions) are at a smaller scale than those typically used to delineate larger "activity systems" (see Engeström, 1987, 1993, 1999), it is our contention that using Engeström's (1987) triangle to explain instances of activity at this scale is useful, meaningful, and, we argue, theoretically consistent with activity theory (Engeström, personal e-mail communication, January 3, 2001). Following the reporting of these actions, the results are then character-

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[1] It is our contention that the overall course structure is a macroreflection of each of these nested interactions, and, thus, we find it useful to apply the triangle at multiple levels of activity, both micro and macro. As others have argued (Knorr-Cetina, 1981; Latour, 1987), each macrolevel unit of analysis can be conceived as a collection of nested microlevel units of analysis. It is partly toward revealing this nested level of activity systems that our Results section is targeted. For example, we intend to capture how on one occasion the VR tool served as the object, only to be "black boxed," closed off for inspection, and used as a tool to enable the participant to have an object at a later date. Black boxed describes the process by which a piece of machinery or a set of commands becomes compiled. At this point, the commands are no longer the focus of the activity but can be used, transparently, to perform some other activity.

ized through a more generalized depiction of the activity system, one that is abstracted from its concrete form (Leont'ev, 1974).

Given that activity systems are characterized by inner contradictions or what we are referring to as *systemic tensions*, the first step in applying this theory as an analytical tool involved clarifying those tensions that characterized the course activity system. For this study, our goal was to identify those tensions that were pervasive (i.e., characterizing the overall course) and to use these systemic tensions as a framework for more focused analyses of specific, momentary interactions during the course. For this article, it was our intention to identify and examine course instances that would serve as exemplars of the broader course tensions and innovations. In identifying these tensions, we examined field notes, interview data, pre–post interviews, and used the database to identify reoccurring 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 participants (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 further used the database and field notes to identify their unfolding through strings of actions throughout the course. Based on the node descriptions in the database and tags in our field notes, we then examined the original videotapes for the complete dialogue. Through an examination of the dialogue, through the constant-comparative method (Glaser & Strauss, 1967), and through prior case study analysis (Barab, Hay, Squire et al., 2000; Barab, Hay, Barnett, & Keating, 2000), we identified the systemic tensions that we viewed as characterizing the course (see Figure 2). Member checks with the course instructor and former students were used to further validate that these were indeed the primary pervasive systemic tensions of the course.

The first dimension of difference and dispute that emerged from our data resulted from the fact that the course incorporated cutting-edge technology. This tension was first apparent in the course development, in which the astronomy professor expressed concern over the fact that learning the technology and building VR worlds would take time away from learning astronomy (Barab, Hay, Squire et al., 2000; Barnett et al., 2001). During data collection and data analysis, especially in the

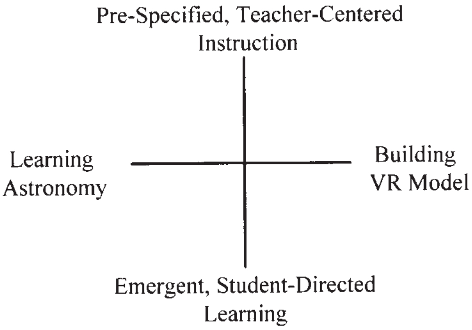

FIGURE 2 Framework for examining the potential of the VSS course to support learning.

spring semester, we identified numerous instances in which there was tension between building VR models and learning astronomy.

The second tension of focus that arose from our data was the role of the instructor in supporting the learning process. This tension involves whether it was the instructor or the students who determined what is to be learned and what steps are taken to promote learning. Specifically, it is the tension between teacher-centered, prespecified instruction on one end and student-directed, emergent learning at the other end. Again, this tension was first apparent in course design and then further apparent during the data collection. Combining these two dimensions resulted in a framework for examining the potential of the VSS course to support learning.

RESULTS AND DISCUSSION

In this section, we use illuminative examples as grounded instances of course activity. In presenting the issues, specifically, we begin with concrete examples from the classroom. These examples are selected based on their being representative of the interactions that emerged with respect to a particular course tension. Each example begins with a brief description of the context surrounding the transcribed section of data. Following the context and transcribed section, we use Engeström's triangle to analyze the specific action, our interpretation of the instance, and how it relates to the overall class activity system. We then include pre- and post-test interviews targeted toward identifying student conceptual understandings to complete the description of the outcome component of the activity system (see Figure 1).

Systemic Tension I: Learning Astronomy versus VR Models

The first tension of focus is on whether building VR models interfered with the students' learning of astronomy. In examining this tension, we provide example actions that are representative of the larger course, and that illuminate both when building VR models facilitated learning astronomy and where it appeared to interfere.

Interrelations of VR Models and Astronomy Understanding

Using models to understand the line of nodes. In this example, Todd is talking to the instructor about the difficulty he is having understanding when eclipses occur, and how to represent them. The instructor suggests that Todd should look at Erica's (a student from another group) 3-D, VR model and see how she used the concept of line of nodes (the line in space formed by the intersection of the ecliptic and the celestial equator in which the Sun, Earth, and Moon must lie if an eclipse is to occur) to demonstrate when eclipses occur. The following dialogue begins when Todd asks Erica how she used line of nodes in her VR model.

Action A

1. Todd There is a rumor that you're working on the line of nodes in your model. I'm not sure what it is?

2. Erica It's where the plane of the ecliptic between the Sun and Earth, and the plane the Earth and Moon intersects … It is not a real line … Whenever the Moon crosses this line [*pointing to the screen*] there is an eclipse … [*Todd nods*]

Action B

3. Erica [*pointing to the screen, continues*] The way I made mine, I made a long cylinder and made it a very long line.
4. Todd Wow, that thing is a cylinder!
5. 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.

Action C

6. 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!
7. Erica This is going to be neat … When I did it last time I grouped it wrong, so be careful.
8. Todd Thanks!

This transcription portrays how multiple actions are nested within each other for a common anticipated outcome—Todd and Erica's understanding of eclipses. Todd, the participant who is engaged in these activities, is determined to obtain a better understanding of when eclipses occur to fulfill the technical rule of the class to represent eclipses in the VR model. Initially, Todd is interested in obtaining the object of understanding when eclipses occur, and asks the instructor who becomes the tool for mediating the participant to obtain the object. Within this action, even though Todd's overall goal is to understand and represent when eclipses occur in his VR model, we see how Todd has broken down his goal to understanding the concept of when eclipses occur and put aside the goal of representing it in his VR model. The instructor, as mediator, suggests Todd consult Erica, who has a representation of the line of nodes in her VR model, so that he can better understand when eclipses occur. Therefore, the outcome of this action is to direct the participant to a new tool (Erica and her model) for obtaining the anticipated outcome. Although not included in this section of data, earlier we recorded instances of Erica working on her model and developing her current understanding of the line of nodes.

Todd then engages in series of actions centered around Erica and her VR model, with the model serving as the object of understanding as well as the tool in supporting understanding the concept. Figure 3 is a graphical representation of Todd engaging in the string of Actions A to C to obtain the anticipated outcome. Throughout these actions, Todd is interested in obtaining different objects in each action but is anticipating obtaining the outcome of understanding when eclipses occur. Initially, Todd (participant) presents himself to Erica (tool) wanting her to mediate his understanding of the astronomical concept of line of nodes (object). In the dialogue that constitutes Action A, Erica provides an explanation of her understanding of the line of nodes and proceeds to introduce her model as another tool for Todd's mediation. As Todd listens to Erica's

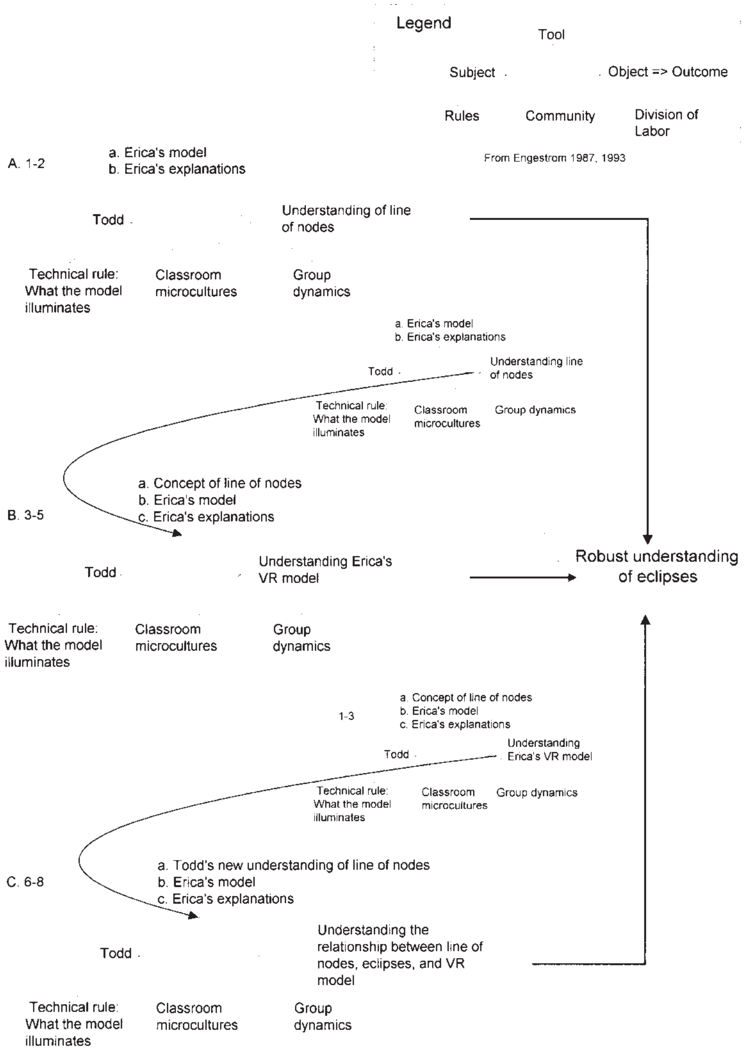

FIGURE 3 Contextual diagram of actions regarding the use of models to understand the line of nodes.

explanations and examines her model, he begins to develop his own understanding of line of nodes. Todd's new understanding is mediated by engaging in an action with Erica, all of which becomes black boxed (no longer an object to be transformed) and is nested as a mediating tool in Action B.

In Action B, Todd (participant) focuses on obtaining the object of understanding Erica's VR model, and how she represented the line of nodes. For Todd to obtain this object he uses his newly developed understanding of the concept of line of nodes. This analysis depicts how an entire action experienced by a participant prior to a newly encountered action can become one of the components, nested, within the next action. Within the scenario, this does not guarantee that Todd has obtained a rich and accurate understanding of the concept of line of nodes, but it demonstrates how a participant can choose to use a newly obtained object regardless of its richness for mediating an action. In Action B, Erica points to her model and shows Todd what technical strategies in CosmoWorlds she used for representing the line of nodes. This helps Todd to have a further understanding of the concept of line of nodes; he expresses this appreciation with "Wow!" In Action C, Todd explains to Erica his new understanding of line of nodes, and how it relates to when eclipses occur. Therefore, in Action C, Todd's new understanding of line of nodes, Erica, and her model all becomes the tool for him to understand the relationship among the line of nodes (the object) and representing it in a VR model.

The similarities and differences between a full moon and a lunar eclipse are elusive astronomical concepts for introductory students. In the preclass interviews, 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 from the ecliptic plane. Todd, a student with minimal science background, next demonstrates his confusion with the cause of lunar eclipses:

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.

In his postinterview statement, Todd utilized two conceptual tools developed during the VR modeling process, the 5-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 then it is an umbral eclipse it is beet red, if it is a 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. This outcome, rich understandings of lunar eclipses, was not unique to Todd. By the end of the course, seven of eight students used the concepts of the Moon's orbital tilt and the line of nodes to explain the Earth–Moon–Sun system (Keating et al., 1999).

Systemic Tension of VR Models and Astronomy Understanding

The tool as object. The following discussion shows how tensions were created and were eventually resolved between understanding astronomy and working on models in the VR course. Kurt and Mandy are struggling to create and animate viewpoints to show the Moon's eclipse. They have omitted one step in the animation process, which is causing CosmoWorlds to reposition their objects. Both of them are unaware that they have skipped this key step and are confused as to why CosmoWorlds is "moving" objects.

Action A

1. Kurt	So you didn't get it back to the right place?
2. Mandy	What happened there? I don't understand. Is that the Earth and Moon?
3. Kurt	I don't know. Why do these things keep moving? Why don't they just do it on the Y? It's real frustrating.
4. Mandy	4.3 5.0
5. Researcher	What do you want to do?
6. Kurt	We want to spin this around that. This is the Earth, this is Moon, and this is the Sun. The problem is that every time we do this thing, numbers just appear from nowhere that you didn't put in, you know? You don't put in anything, you don't move anything. It's so frustrating to me. It's really bothering me. [*pause for a few seconds, as Kurt works with his model*]. So that's right, but now what? See that one [*the viewpoint*] wasn't even there last time. It was point something. Now, it's [*CosmoWorlds*] made something else up. So the distance is right. Where did these [*distances created by CosmoWorlds*] come from? So now I'm gonna change it down to zero. [*pause*] Not to mention that the scale to size is whacked out every time. I don't know if I should change them, or just assume they're right. I don't know where they get these things, because I never put those numbers in, you know?

In this segment, we see how the VR tools become the object of the action. Kurt is clearly struggling to understand how to use the tool. He would like to model the Moon's eclipse. He knows precisely where the viewpoint cameras should go but is unable to physically place them in the desired position. He is quite frustrated, as his inability to use the tool is interfering with his ability to build his model and demonstrate astronomical concepts. The next passage exemplifies the group's frustration.

Action B

7. Kurt	Can I drop this class? [*then, to the computer*] C'mon please?
8. Mandy	This is a lot harder class than the other two astronomy classes I took. No one helps.
9. Kurt	If you move it, it's gonna get messed up. [*pause for 20 seconds*] How are you doing, Sam?
10. Sam	OK. How are you doing?
11. Kurt	[*Kurt gives him the "thumbs down" pauses*.] "Very frustrating. CosmoWorlds won't do anything I tell it to do."

In Action A, Kurt is struggling with the tool and object CosmoWorlds (see Figure 4, Action A). Because of this frustration, the outcome, he publicly considers dropping the course. Mandy seems to agree and adds her dissatisfaction about the amount of support available in the course. In commenting that CosmoWorlds "won't do anything I tell it to," Kurt shows that CosmoWorlds is the object of his action. He is trying to learn to use CosmoWorlds as a tool. However, due to his lack of experience, CosmoWorlds is simultaneously the object and the tool of this action.

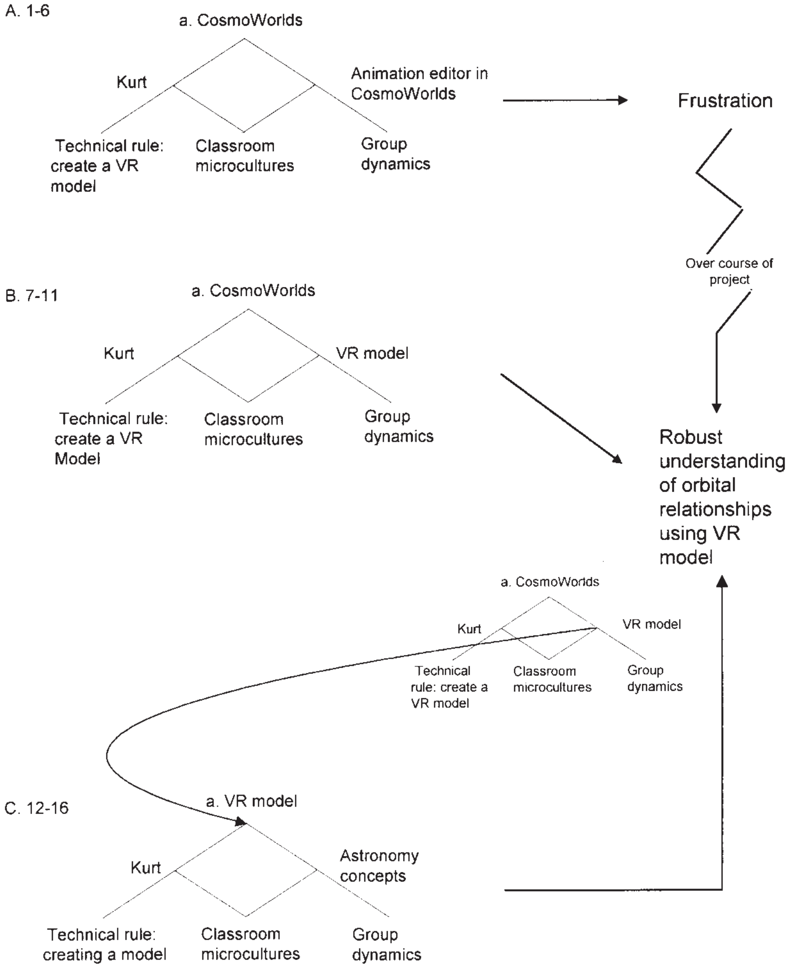

FIGURE 4 Contextual diagram of actions regarding systemic tension of VR tools and astronomy understanding.

Understanding viewpoints played a critical role in the modeling process. Over the course of the project, Kurt became skillful at placing viewpoints and using CosmoWorlds as a tool to develop his model. With this newly developed skill, Kurt spent the first 30 min of the next class (*Action B*), using the animation editor of CosmoWorlds to add viewpoints to his model. As the model approached completion, Kurt began to shift his focus from building the model to enhancing the model in depicting astronomical phenomena. In the following passage, Kurt is using viewpoints along with the animation editor to demonstrate astronomical concepts in his model. Kurt has just set a viewpoint on Mercury looking out towards the solar system.

Action C

12. Kurt No way, that is so cool. Hey, look [*to Mandy*] you know what's happening?
13. Mandy [*says nothing*]
14. Kurt All the others are standing completely still and Mercury is spinning.
15. Mandy Oh, that's awesome!
16. Kurt Finally, something you can see, you know?

In Action B, Kurt (the participant) used CosmoWorlds (the tool) to complete his VR model (the object). Following this, in Action C, Kurt the participant has begun using his VR model as a tool to explore astronomical concepts. By setting a camera on Mercury, he made the model demonstrate how quickly Mercury is spinning, and how quickly it revolves around the Sun. Through this action, he has taken a relatively static concept from the textbook and explored its dynamic relationship with respect to the solar system through the model. In other words, using the model has allowed him to visualize the concept of Mercury's day and year. Over the next 2 days, Kurt created 23 other viewpoints designed to highlight astronomical phenomena, including the Pluto and Charon system, Neptune's unusual elliptical orbit, the relative size and distances of the planets, and the relative length of each planet's day and year. Thus, expanding the model beyond just a static depiction of the planets to include viewpoints allowed Kurt to develop a robust understanding of orbital relationships as the *outcome* of Action B.

Modeling scale. The following dialogue illustrates how students decided to create multiple models to represent eclipses and phases of the Moon.

Action A

1. Instructor So how is your scale model going?
2. Jessica It is going OK, but look at this. We have used the Earth's diameter to help us scale them [*the Sun, Moon and Earth*], but we can't see anything!
3. Instructor Have you tried to line them up on the X-axis and zoom out to try to see them?

Action B

4. Steve No, we haven't, but still the Moon is so far away from the Earth. I don't think we can show anything about the eclipses or phases.
5. Instructor You could try a different scale.

Action C

6. Jessica But we have worked so long on this one.
7. Steve Is it possible to use a different scale for the sizes and the distances?
8. Instructor You can, but just make sure you acknowledge the shortcomings in your model.
9. Steve Sure, we can keep the one to scale and use this one [*the model not to scale*] to present.

10. Instructor OK, sounds good to me, just remember the shortcomings of your model.

The technical rule of this project was to demonstrate phases of the Moon and eclipses as part of a scaled model of the Earth–Moon–Sun system. From this rule, a tension emerged between creating a model that demonstrated phases of the Moon and eclipses on the one hand, and on the other hand, an accurate representation of scale. In this example, we see how the participant, Jessica and Steve, who together constitute what we referred to as “Team Yellow,” struggles with this tension. In Action A, Team Yellow recognizes the inadequacy of the scaled model in representing eclipses and the phases of the moon (see Figure 5). After examining the accurately scaled model, which is the

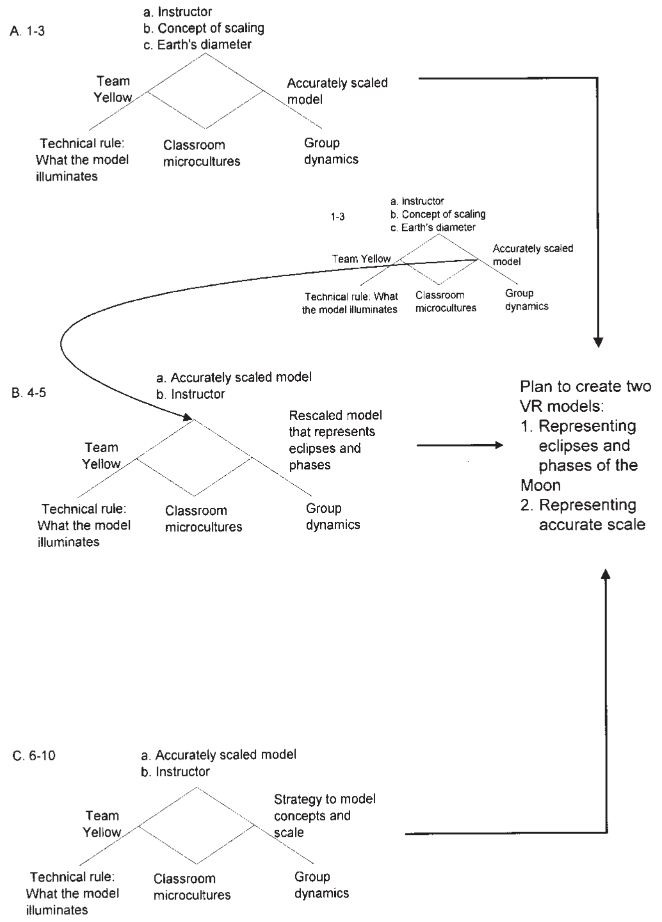

FIGURE 5 Contextual diagram of actions regarding systemic tension of VR tools and representing accurate astronomy concepts.

tool in Action B, the participant decides that they need a rescaled model that would represent eclipses and the phases of the Moon. In Action C, the participant obtains a strategy for creating a model that does not accurately represent all aspects of scaling but does represent eclipses and the phases of the Moon. In this example, the outcome of the action is the participant's recognition that two models are needed to represent all relevant astronomy concepts.

In the course there was a tension between fostering student development of VR models that represent, demonstrate, or explain some astronomical phenomenon, and the students constructing a compromised model that appears aesthetically pleasing. This tension is not always desirable, as it proved to be detrimental to some students' comprehension of astronomy. For example, the Earth–Moon–Sun system project involved modeling the distance and size relationship among the three objects. However, the previous example illuminates how when students constructed their model to scale, they were uncomfortable with the results because the model, though accurate, was not very easy to see and explore on their desktops.

Therefore, students frequently either compromised the astronomical accuracy of their original model (as just occurred), or developed one model for class presentations and one that was conceptually accurate (also occurring earlier). This procedure of creating two models did indeed allow the students to construct models that looked aesthetically pleasing, and did have utility in representing astronomical concepts. For example, as evident in Todd's previous description, students successfully modeled and, in posttest interviews, competently answered questions regarding how eclipses occur and whether the Earth has phases when viewed from the Moon.

Most students, however, maintained an inadequate appreciation of the distance scale between objects in the solar system. For example, Jessica never went beyond a tenuous understanding of the relative scale of the solar system as evident in the postinterview:

Interviewer	So far we have a scale of the size of the planets, is that the scale of distance?
Jessica	No.
Interviewer	Say the Sun was that size [*the size of a grapefruit*], how many planets could I fit on these two boards?
Jessica	I could guess, like, big time. Oh gee, in my model I had to make the Sun smaller because it was eating Mercury. When I did it to scale, I couldn't even see Mercury. And that was almost the same. I'm just completely guessing. [*she spreads out the objects in the classroom*] I'm basically just spreading them out evenly.
Interviewer	How many planets could you get on these two boards if drawn to the scale to the Sun?
Jessica	To scale, I don't think we would get very far unless we cut down the scale. With the Sun that big. I think we might get to Mars because there is a lot of space in between there. There are big distances, I know that.

This dialogue clearly illuminates Jessica's limited understanding. For example, when asked to articulate the scale of the solar system, Jessica resorted to guessing and admitted that she did not have a firm grasp of the concepts.

Another student, Dave, who like Jessica had an aesthetically pleasing but astronomically inaccurate model, also struggled with issues of scale in the post interview.

Dave [*going to the whiteboard*]. Do you want the scale of size?
Interviewer Well, I really want the scale of size and the scale of distance, but tell me what you think. How would you do it? So if you were to draw the Sun that big, how many planets would you fit distance-wise in this room?
Dave [*struggling with scale*.] I'd probably take it to that door to draw it correctly. Because we were trying to do it correctly in our model and it was just impossible. We had to completely change scale

In this quote, Dave expresses his frustration trying to model the scale of the solar system with CosmoWorlds. Given the vast distances between planets, the student groups were forced to compromise the accuracy of their model to be able to present a visually pleasing, monitor-screen size presentation. This resulted in a limited appreciation for the scale of the solar system by four of the eight students in the post-test interviews (Keating et al., 1999). As the previous examples indicate, the tension between aesthetics and accuracy frequently led to the outcome of limited astronomical understandings of size and scale relations.

Systemic Tension II: Prespecified, Teacher-Centered versus Emergent, Student-Directed Constraints

The second systemic tension focuses on the origin of course constraints. On the one hand, it was our intention to support student ownership, and on the other, we clearly had specific astronomy knowledge that we intended that students learn. In examining this duality, we looked at instances in which students did not develop constraints, as well as those instances in which task constraints did emerge.

Prespecified, Inert Expectations and Shared Labor

Failed project from poor planning. As a general rule, students begin the first project by defining their own methods and means of reaching their final goal. For example, during the first project, student groups just proceeded ahead, paying little attention to planning their tasks and to division of labor. However, over time, the instructor suggests that the students keep a record of their progress, the facts being used to construct the model, and the data of their model such as the position of their planets in the model. The instructor also suggests that the project would probably be most efficiently done if the groups divide tasks.

Action A

1. Beth I think we should probably work together, because that way we will always know what each of us is doing.
2. Kate OK. Any ideas on what we need to do?
3. Beth No, I guess we probably should read and find out about the Earth.
4. Kate OK.

5. Instructor [*about 10 minutes later*] How are you doing? Do you have any questions concerning the project?
6. Beth No, though I think we are going to work together first, because it looks like we can make a better project with both of us working on the same thing.

Action B

7. Beth Something is wrong with our project, we can't move the Earth.
8. Instructor Do you know the position of the Earth?
9. Beth No, we have moved its center to the Sun and it only says 0,0,0. [*showing her frustration*]
10. Instructor OK, let's see if we can figure it out. Do you know the position of your Sun?
11. Kate I think it is at 0,0,0.
12. Instructor OK, now do you have the position of the Earth written down?
13. Beth No.
14. Kate That would probably have helped us.

Action C

15. Instructor Yes, maybe in the future you should, because it [project plan] will solve problems like you are having now and it is good scientific practice.
16. Beth Well, what do you think we should do? Maybe just start again, but this time keep the data.
17. Instructor Has your team decided on who would be the note taker?
18. Kate No, I guess I can be.
19. Beth OK, then let's just start over and this time we will write everything down!

Action D

20. Team [*Students then proceed to work on their model with Kate as note taker*.]

In Action A, to fulfill the technical rule of working in groups, the subject Kate and Beth, who together constitute what we referred to as "Team Blue") in collaboration with the instructor and each other (the tools) try to develop a project plan (the object) (see Figure 6). Then in Action B (next), Team Blue recognized the need to develop a project plan. In Action B, the participant (Team Blue) was frustrated with the tool (CosmoWorlds), because it hampered their ability to create the object (VR model). This awareness by the group led them to consider keeping a record of their work. In Action C, they consult with the instructor (the tool) to create team roles (the object). Last, in Action D we see how these new roles and rules feed back into this new iteration of student action.

The earlier dialogue is an example of the more general outcome that, overall, groups did not plan for their first project (see Barab, Hay, Barnett, & Keating, 2000). Instead, the projects were haphazard, incomplete, and of lower quality than the second and third projects. Using the database, we found that for the spring semester, students had only 22 episodes related to planning during the first project and 144 episodes for the second project. Furthermore, in the first project,

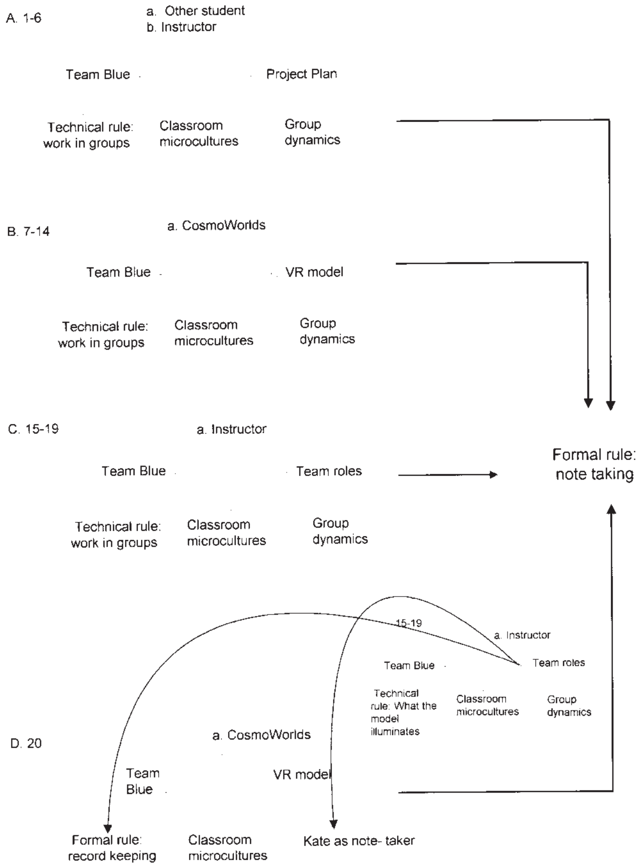

FIGURE 6 Contextual diagram of actions regarding poor planning and a failed project.

students did not begin planning until day 4, while in the second project they had 25 episodes related to planning at the same point. Based on their experience with the first model, students took ownership and proceeded in a more systematic manner for Project No. 2. In this way, the outcome of the first system, poor project results fed back into the system and project planning became a tool each group utilized in Project No. 2.

Emergent Expectations and Distributed Division of Labor

Developing a plan. In the first project, students worked collaboratively to develop a model of the Celestial Sphere. However, there was little systematic planning and students expressed dissatisfaction with the quality of their first model. Kurt summed up his experiences in Project No. 1, "I'm not very excited about this one, but the next one has to be better." The following dialogue describes the beginning of the second project.

Action A

1. Kurt OK, I have put down everything I think we need to do to complete the second project. Is there anything I am missing?
2. Instructor I can't think of anything, it looks very good.
3. Mandy OK, so you have the scales of the planets already done too?
4. Kurt Yes, I just used the table in the book and multiplied those numbers by 10.
5. Instructor Sounds good.

Action B

6. Mandy OK, so what do you want me to do?
7. Kurt It depends. What do you want to do?
8. Mandy Let me see that [*pointing to the document*]. I think I want to do Saturn, and maybe Jupiter.
9. Kurt OK, I will work on a scale model.

In Action A, Kurt, the participant, is using his textbook and mathematical skills as tools to create a table of scaled distances for their model, the object (see Figure 7). The table of scaled distances shifts from being the object in Action A to being a tool in Action B. Using this table, the subject,

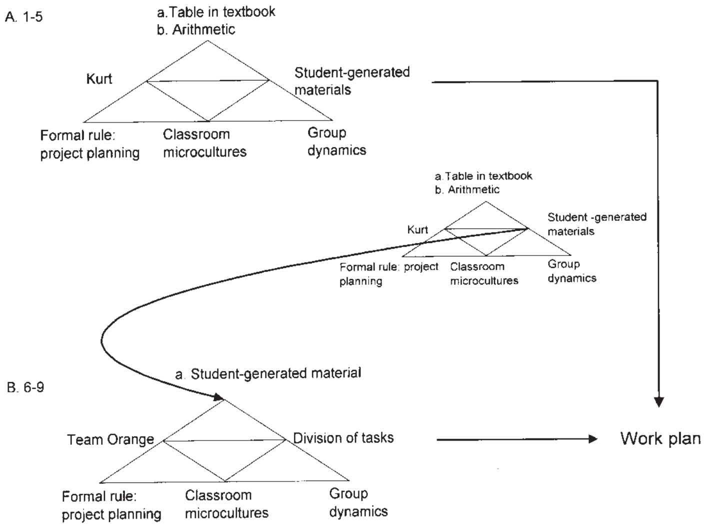

FIGURE 7 Contextual diagram of actions regarding the development of a plan.

Team Orange, develops a strategy to divide tasks, the object. This led to the overall work plan, the outcome. This document became a formal plan, as well as influenced future division of labor.

The assignment of the tasks to individuals, though a good practice for accomplishing tasks as team, was not as successful for fostering the development of a broad understanding of astronomy. For example, during the posttest interviews, several students could not describe the composition of Jupiter, because a different team member was solely responsible for investigating and modeling the interiors (divisions of labor*)*. The following excerpt is taken from a student's follow-up interview:

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, Mike [*the instructor*] saying that if Jupiter was a little bigger it would be a star. There you go.

The outcome of some students having limited understandings of planetary composition was a result of the division of labor in which not all students worked on all parts of the project. This tension in outcomes led to changed rules and expectations in future iterations of the course, as all students were required to both construct planetary interiors and model the dynamics of the entire solar system.

Class expectations regarding presentations. At the end of each project, student teams were expected to present their models to the entire class. The students were encouraged to focus on the astronomy content in their models during the presentations. Initially the presentations were not considered a vital part of the project by the students. Consequently, there was little evidence of planning. According to the instructor, all groups delivered substandard presentations for Project No. 1. Following their presentations, most groups met to discuss their concerns about the quality of their performance. In the dialogue that follows, team members plan their presentation for the second project. It is evident from the dialogue, as well as instructor comments, that their initial presentation was unsuccessful (see Action D, 14), and that this was part of the impetus for the increased preparation for the second presentation.

Action A

1. Taro OK, we have to get ready for the presentation. What are we going to do?
2. Todd We should describe your logarithm scale, because that is different. I don't think other teams did it.
3. Taro OK, don't worry. I can do that.

Action B

4. Taro How about your model?

5. Todd It is OK, I would like it to be better.
6. Taro Yes, but can you explain it? Let’s see if you can. Tell me about it.

Action C

7. Todd These planes represent, well let me think, the ecliptic, and the Moon’s orbit I think.
8. Taro OK, but why?
9. Todd I was going to discuss the line of nodes!

Action D

10. Taro [*asking Bob*] Are you are going to present the Sun? What do you know about it?
11. Bob I know, and I have read the book.
12. Taro Let’s find more [*begins looking up the Sun in his textbook*]. We need a good presentation. Do you know what this is? [*pointing to a figure showing a photon’s path out of the Su*n]
13. Bob OK, I know about that, it is the random walk thing that you told me about.
14. Taro OK, sounds good. It has to be better than last time.
15. Todd I sure hope so. The last presentation was terrible.

Postpresentation

16. Taro [*shaking Todd’s hand*] Much better, much better.
17. Todd Yes, it sure is much better.

In Action A, the participants, Todd, Bob, and Taro, who together we referred to as “Team Green,” are discussing their VR model and scaling methods, the tools, for satisfying the formal rule that every presentation, the object, has unique aspects (see Figure 8). Although the group does not discuss their previous problematic presentation until lines 14 and 15, this experience clearly is driving the planning and preparation of their current presentation. This discussion continues in Action B where the participant Todd is trying to articulate his understanding of the model, the object, with the help of Taro, the tool. In Action C, Todd identifies the plane of the ecliptic and the line of nodes, the tools, as the critical astronomy concepts for his understanding, the object, for a successful presentation, formal rule, that describes the model. In Action D, Bob, the subject, is being challenged by Taro, the tool, to explain his understanding of his model of the Sun. Taro, the tool, assists Bob in locating more information in the textbook, a tool, for the intent of preparing a successful presentation, the object. As shown in lines 16 and 17, this string of actions led to the outcome of a self-satisfying presentation.

CONCLUSIONS AND SUMMARY

There are many different transformations that a participant can have on an object. To some degree, it is the participant’s goals and intentions that provide boundary conditions, constraining which

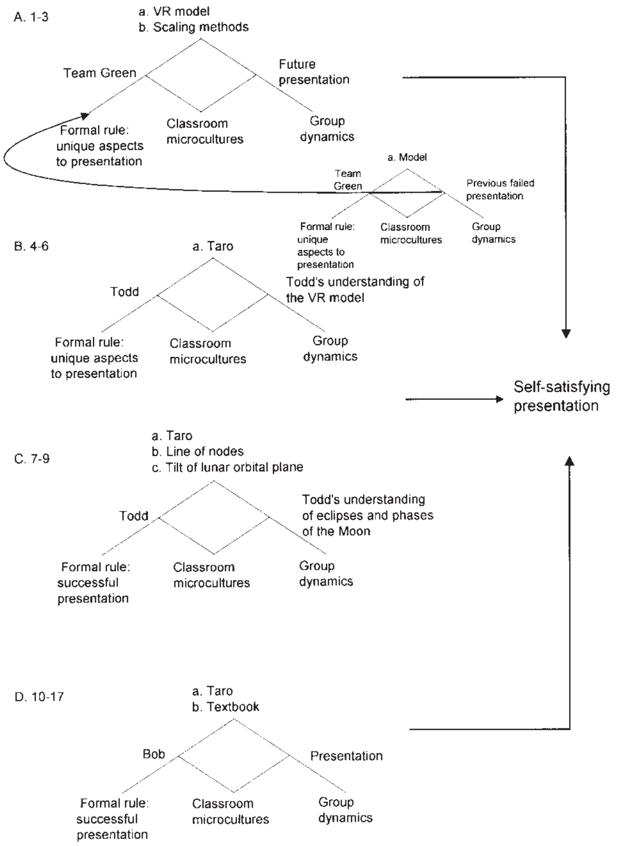

FIGURE 8 Contextual diagram of actions regarding preparing for a presentation.

particular affordances (opportunities for action) of the object the activity will transform (Barab & Plucker, 2002). However, the relations between participant and object are also mediated by various factors, including tools, community, rules, and division of labor (see Engeström, 1987, 1993). All these factors influence learner intentions as well as provide additional constraints. They simultaneously enable and limit relations between participant and object and the potential transformations and understandings of an object (Barab, in press). For this course, we focused on the relations of participant and object and how object transformations frequently involved scientific understandings. These transformations were mediated by tools (both technological and human), the overall classroom microculture (emergent norms), division of labor (group dynamics and student–instructor roles), and rules (informal, formal, and technical). Of primary concern were how these factors supported the participant's transformation of astronomy content into virtual models and astronomical understandings. What began as intermediate hypothesis in terms of the pervasive systemic tensions driving course activity were enriched through detailed empirical analyses in which we documented their manifestation in student actions.

Beginning with the first hypothesized system tension, instead of detracting from the emergence of an activity system that supported learning astronomy, the building of 3-D models frequently constituted learning astronomy suggesting that the role of the instructor is not to eliminate this tension but to balance the interplay among the dimensions. For example, we continually witnessed where the constructing of students models (the object) or the use of models as tools to visualize an astronomy concept (the object) provided a means of learning astronomy. This was evident in the first example where it was apparent that Todd's working on modeling the line of nodes helped his understanding of eclipses. Todd even referred to this model in the follow-up interview when asked to describe why eclipses occur. This is not to imply that there was no tension. For example, we saw the increasing frustration expressed by Kurt and Mandy during the spring semester in which Kurt expressed a desire to drop the class. The introduction of the Celestial Sphere project in the following summer (discussed earlier in the Curricular Evolution section) appeared to have lessened the frustrations surrounding learning the technology in that students modeling the less dynamic Celestial Sphere did not have to learn the technology while at the same time having to model complex dynamical interactions. Again, the challenge is not to eliminate systemic tensions but to balance the interplay so that it enriches system dynamics and facilitates motivation and learning.

With respect to the tension between prespecified, teacher-directed instruction and emergent, student-directed learning, the component that most directly influenced the course activity system was the object, suggesting that our course should not be conceived of as student directed or teacher directed, but as object directed. This was evident, for example, in the fact that most of the groups did not begin planning until Project No. 2 when it became apparent during the first presentations that this was necessary if they were going to produce high quality models (objects). Student models provided a shareable phenomenon, serving to constrain course activity toward those practices that most effectively supported the transformation of the object into a model that was consistent with how scientists' described the phenomenon. In setting up this system of object transformation, it is the responsibility of the teacher to seed the system's emergence and to support students in developing their own constraints (Barab, Squire, & Dueber, 2000). This was partly accomplished through student-developed questions to be addressed by their models but also involved the continual support of the teacher who used his astronomy expertise to push the object transformations in a manner that was consistent with those practices being advocated by the scientific community. In this way, the instructor was most often a tool supporting student activity.

Reflecting this analyses, we interpret the various course tensions and innovations in the framework of the overall course activity system, modeled in general form in Figure 9. In this figure, we found the pervasive tensions of the course characterized in the form of dilemmas within each component of the triangle (e.g., participant: passive recipient vs. engaged learner). There were also manifestations that occurred across components (see a, b, c in Figure 9) all of which originated in the object component, indicating that the tension of, and between, building VR models and learning astronomy were tensions that took on various expressions. More important, we argue that this tension (and innovation) forming around the object provided the central impetus for the evolution of the course activity system. For example, the activity system produced tensions between building dynamic VR models and building models to support astronomical understandings. Recognizing this tension, the course is now conceptualized as a modeling-centered course. In this way, tensions fueled the evolution of the system.

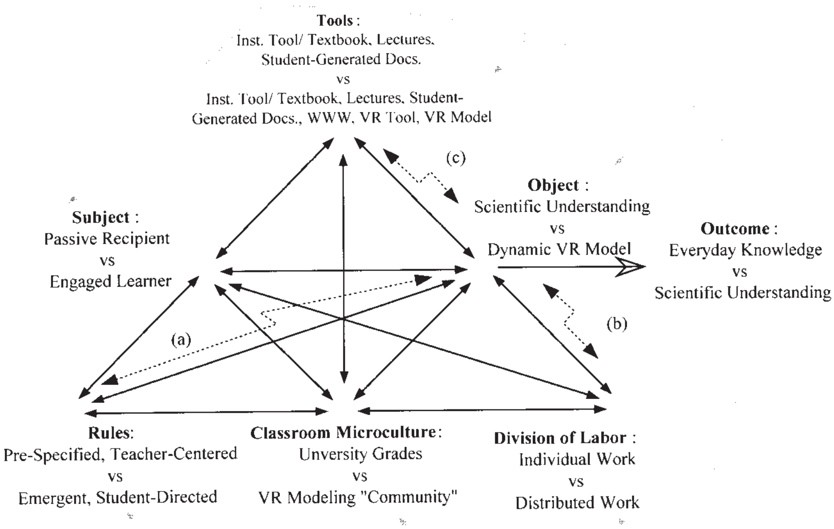

FIGURE 9 Pervasive systemic tensions of the course activity of students participating in the VSS course.

It is important to note that Figure 9 is a macroreflection that, to some degree, obscures the multiple and varied strings of actions that characterize course activity in situ. Thus, the model of their activity system we present in Figure 9 is not a static model. Rather, it is a model continually in the making (Latour, 1987). In other words, Figure 9 has a history, nested instances of activity, which when viewed from different vantage points and from different points in time, may be construed and represented differently. For example, in Figure 3, lines of nodes transformed from objects to tools. Similarly, in Figure 6, the project plan evolved from being the object of the action to formal rules and expectations operating in the activity system. Thus, Figure 9, the general depiction of the activity system, tends to neglect the dynamic, evolving nature of activity systems. As we have demonstrated in this article, it is not the static model, but rather the trajectory of the system through time, that makes activity theory a useful theoretical lens for characterizing activity. By understanding the systemic tensions driving evolution in a system and the outcomes of a system, researchers can help inform the evolution of a system. In our case, this meant introducing new tools, modifying rules and expectations, or modifying divisions of labor to facilitate the production of new outcomes. Changing activity systems that occur across extended time frames in general ways must be treated with caution, and we argue that simply presenting Figure 9 would drastically misrepresent the contextualized nuances that are central to learning trajectories as supported through participatory learning environments.

IMPLICATIONS

Currently, we are moving from cognitive theories that emphasize individual thinkers and their isolated minds to theories that emphasize the situated nature of cognition and meaning (Barab &

Plucker, 2002). In general, situative perspectives suggest a reformulation of learning in which practice is not conceived of as independent of learning and in which meaning is not conceived of as separate from the practices and contexts in which they are developed (Greeno, 1998; Lave & Wenger, 1991; Resnick, 1987; Young, 1993). In the development of our course, we have accounted for the contextually-bound nature of cognition by situating learning within the context of a rich activity system (see Figure 9). As such, the outcome of learning is not simply the memorization of abstracted content and meanings generated by someone else. In many courses, the primary instructional activities involve lecturing by the instructor with students memorizing texts and their notes to be exchanged for a grade. In this context it is the students that are considered the object of change (Lave & Wenger, 1991). In contrast, we have immersed and supported the learner in creating a participatory learning context that positions students as participant, not objects, driving their course activity.

In our course, we (the designers, the instructors, the students) have worked to establish an environment that supports students in building their astronomy models and their robust understandings. It is essential that designers concern themselves with how to support the emergence of actions that allow students to own the outcomes, and to support students in constructing outcomes that are scientifically accurate. "The more the teacher, the curriculum, the texts, and the lessons 'own' the problems or decompose steps so as to push learners away from owning problems, the harder it may be for them to develop the practice" (Lave, 1997, p. 33). Rather then transmitting knowledge, we view the role of the instructor as seeding the emergence and facilitating the continual evolution of a system whose function is directed by students toward actions that support learning the material in question.

In this research, we used activity theory as both a theoretical lens as well as an analytical tool for understanding the pervasive course tensions. In contrast to analysis methods that treat interacting system components in isolation, activity theory provided us a means of characterizing the complexities of course dynamics. Viewing the class as an activity system allowed us to understand how dualities, analyzed as systemic tensions, led to outcomes that were inconsistent with students developing astronomical understandings. An appreciation of these tensions fueled changes in the course as discussed in the Curricular Evolution section. For example, tools to help students use the technology, expectations (seed and base questions) that required students to confront concepts like the line of nodes, or expectations that brought about new divisions of labor as all students had to know all aspects of their project.

In building and supporting the continual unfolding of activity systems designed to support learning educators need to recognize and harness systemic tensions, identify how they affect the classroom culture, and especially learning goals, balance their influence, minimize potentially damaging conflicts, and allow the system to evolve as the students learn how to balance system tensions (Barab, Barnett, & Squire, in press). This process involves working with the learner, as part of a system, to balance frustration so that the interplay among tension dimensions (learning technology vs. learning astronomy or prespecified, teacher-directed instruction vs. emergent, student-directed learning) facilitate meaningful learning and engagement, not annoyance and dissatisfaction. When educators go to extremes (e.g., entirely discovery-based learning) they miss out on the powerful system dynamics that can be harnessed to support and engage learning. In contrast, when systemic tensions are brought into a healthy balance they can facilitate a meaningful interplay that enriches and adds dynamism to the learning process. Educators might also exploit systemic tensions, discussing these with learners to facilitate their meta-contextual understanding of the learning context.

In this article, we used activity theory to illuminate how our course supported the emergence of actions that transformed objects through which students, as participants in these systems, developed astronomical understandings. The tensions between understanding technology versus understanding course content and between teacher, prespecified instruction versus emergent, student-directed instruction provided a useful framework for characterizing our course. Determining which goal-directed objects will best support the emergence of robust actions is the challenge for instructional designers and educational researchers alike. Armed with this information, educators can redesign courses and work with students to support meaningful participation.

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