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Constructing Virtual Worlds: Tracing the Historical Development of Learner Practices

Sasha A. Barab
Indiana University
Instructional Systems Technology

Kenneth E. Hay
Learning and Performance Support Laboratory
University of Georgia

Michael Barnett and Kurt Squire
Indiana University
Instructional Systems Technology

This study explores learning and instruction within a technology-rich, collaborative, participatory learning environment by tracking the emergence of shared understanding and products through student and teacher practices. The focus is not only on the interactions among students or between students and teachers, but on student–resource interactions, especially student–technology interactions. In a 1-week camp, students worked in activity groups with 3-dimensional modeling software to develop virtual worlds. Holistic accounts of 2 activity groups in the camp are presented, emphasizing the focus of the activity, group dynamics including the role of the teacher, and the historical development of learner practices. Then, a network methodology is used to trace the history of interactions accounting for the emergence, evolution, and diffusion of learner practices. The findings suggest that becoming knowledgeably skillful with respect to a particular practice or concept is a multigenerational process, evolving in terms of contextual demands and available resources. The tracings further reveal the reciprocal nature of learning and doing, with building conceptual understanding occurring in relation to local conditions and practices, and doing practices being a part of student learning.

Requests for reprints should be sent to Sasha A. Barab, School of Education, Room 2232, 201 N. Rose Ave., Bloomington, IN 47405. E-mail: sbarab@indiana.edu

> We are so accustomed to the separation of knowledge from doing and making that we fail to recognize how it controls our conceptions of mind, of consciousness and of reflective inquiry.
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> John Dewey (1929, p. 22)

An increasing number of educators are abandoning predominantly didactic, lecture-based modes of instruction and moving toward more learner-centered models in which students, frequently in collaboration with peers, are engaged in problem solving and inquiry (Barab & Duffy, 2000; Hay & Barab, in press-b; Land & Hannafin, 1996; Roth, 1996). Although some forms of direct instruction are effective for the achievement of specific objectives (e.g., direct instruction of reading strategies; Rosenshine, 1986), the same practices that make these approaches beneficial (e.g., eliminating extraneous information and telling students correct answers) may be inadvertently causing the knowledge to become inert (Cognition and Technology Group at Vanderbilt [CTGV], 1990; Whitehead, 1929). Furthermore, it has been argued that such approaches have the ancillary effect of stifling creativity and diminishing enthusiasm (Cordova & Lepper, 1996).

In response to the limitations of teacher-centered or lecture-based learning environments, the participatory learning environments (PLEs), which we have been developing, support natural complexity of content, avoid over simplification of relations, engage students in the construction of products requiring practices that embody complex concepts, necessitate collaboration, and contextualize learning within contexts in which problem solving and inquiry are fundamental aspects of the learning process (Barab, Hay, Barnett, & Keating, 2000; Barab, Hay, Squire, et al., 2000). Predicated on a social constructivist philosophy, the role of teacher switches from one of telling students correct answers to guiding student activity, as students direct their own learning process (Bednar, Cunningham, Duffy, & Perry, 1992; Dewey, 1938/1963; Edwards, 1995; Prawat & Floden, 1994; Vygotsky, 1978). Consistent with Papert’s (1991) constructionist pedagogical framework, PLEs frequently involve learners building understanding through the collaborative construction of an artifact or shareable product. Rather than presenting instructional treatments, the goal from this perspective is to establish rich environments that encourage explanation and discovery, nurture reflection, and support students in the carrying out of practices that embody personally meaningful and practically functional representations.

The focal point of PLEs is the learners’ emergent practices in relation to the need at hand; it is a move from a “teacher curriculum” to a “learner curriculum” (Lave & Wenger, 1991), or from an acquisition metaphor to a participatory metaphor (Sfard, 1998). Such an emphasis shifts the focus from the individual as a “person to be changed” to how to facilitate the emergent practices of learners working collaboratively, with particular emphasis on the learners’ reasons for carrying out the activities and the context in which they are nested (Lave & Wenger, 1991; Roth, 1996, 1998). Learning is conceived of as a “social process in which meaning is negotiated, goals emerge from social processes, and success is taken within context” (Young, Barab, & Garrett, 2000, p. 160). Learning, from this perspective, is not the acquisition of facts and skills, but an activity involving the appropriation and construction of socially negotiated practices, understanding, and meanings through participation in a trajectory of experience.

This emphasis on the social negotiation of practice has led us to examine students working collaboratively in activity groups to complete a shared task. An *activity group* is a temporary coming together of people around a particular task (Barab & Duffy, 2000). When working as part of our activity groups, learners are frequently given a general description of a task (e.g., construct a virtual reality [VR] play or solar system) and expected to work collaboratively in determining how to best complete the shared task. Various activity groups might share a common goal and even participate under a common pedagogical framework but construct different final products, as well as procedures for getting there, and, reciprocally, have different group dynamics. A focus of this research is to empirically investigate these dynamics and, in response to Dewey’s (1929, p. 22) quote cited earlier, support the claim that knowing and doing are inextricably linked and should be treated as such.

Although there is a growing theoretical base from which to derive principles for the design of PLEs (Barab & Duffy, 2000; Choi & Hannafin, 1995; Duffy & Jonassen, 1992; Jonassen & Land, 2000; Land & Hannafin, 1996; Reigeluth, 1999; Savery & Duffy, 1996; Young, 1993), it is also important to provide an empirical base to ground this perspective. In this study, we use naturalistic inquiry to build a holistic account of two groups of learners participating in a 1-week camp. We also use a network approach to trace the historical development of two practices, both of which involve conceptually rich understanding. Our central goal is to provide empirical support for the claim that within a well-constructed PLE, conceptual understanding and practice are so interrelated that it is meaningless to talk about them as separate entities.

EMERGING TECHNOLOGIES AND VR

Although PLEs can come in many shapes and incorporate various resources, we focus on technology-rich environments that allow students to ground their understanding within their concrete experiences—what we refer to as technology-rich, inquiry-based PLEs for grounding understanding (Barab, Hay, Squire, et al., 2000). These environments take advantage of emerging technologies to establish PLEs that immerse students within contexts that challenge; ground; and, ultimately, extend their understanding. More specifically, these environments:

- Are technology-rich—integrating technology as a tool for facilitating inquiry, other forms of authentic practice, or both.
- Provide opportunities for students to inquire into the phenomena they are learning and not simply receive information about the phenomena.
- Support students in participating in, not didactically hearing about, domain-related practices.
- Are designed to support the process of learning.
- Establish rich environments (studios, workshops, and construction spaces) where students work collaboratively.
- Immerse students in a context that grounds their understanding to local environmental particulars.

Currently, we are seeing the proliferation of emerging technologies that function less like books, films, journals, and broadcasts and more like laboratories, workshops, offices, and studios in which students immerse themselves within contexts that challenge and extend their understanding (Allen & Otto, 1996). Many such environments have been discussed in the literature (Barab, Hay, Barnett, & Keating, 2000; Barab, Hay, & Duffy, 1998; CTGV, 1990, 1993; Edwards, 1995; Jonassen, 1996; Scardamalia & Bereiter, 1993–1994). Central to these various contexts is an active learner who is engaged in practices in which understandings are situated. One technology with considerable potential for grounding understanding in rich learning environments is VR (Dede, Salzman, Loftin, & Sprague, 1999; McLellan, 1996; Winn, 1995).

VR refers to synthetic, computer-based, three-dimensional worlds. VR can either be immersive, in which the user wears a head-mounted display unit, or a "window on the world," in which the technology simulates a three-dimensional environment on a two-dimensional screen (McLellan, 1996). VR has the potential to engage learners in various situations (from a delicate strand of DNA to the surface of Mars), aiding individuals in collaborating with humans thousands of miles away (in adventure educational projects and games), allowing learners to visualize unseen phenomena (atmospheric phenomena related to temperature, humidity, air pressure, and wind velocity), and bringing museum artifacts to the hands of learners. Although the educational potential of VR is considerable, to date, this technology has been used primarily by the military as a tool to train pilots and soldiers in complex simulators. In these contexts, pilots and soldiers are engaged in real-world simulations in which they have an opportunity to experience and learn. Only recently have educators working with kindergarten through Grade-12 students begun to explore the educational possibilities of VR learning environments. Three innovative projects are George Mason University's ScienceSpace (Dede et al., 1999), Georgia Tech's Virtual Gorilla Project (Allison, Wills, Hodges, & Wineman, 1997), and the University of Washington's Virtual Reality Roving Vehicle (VRRV) and Virtual Puget Sound projects (Windschitl & Winn, 2000; Winn, 1995).

The Virtual Gorilla Project and the ScienceSpace project, although innovative and educationally rich, follow the military–aviation model of immersing learners in predeveloped VR worlds. In contrast, learners using the University of Washington's VRRV are able to construct their own virtual worlds in areas such as AIDS education (Bricken & Byrne, 1993), the wetland cycle (Osberg, Winn, Rose, Hollander, & Hoffman, 1997), and other domains (Winn, 1995). Underlying the University of Washington's perspective of how VR should be used is a constructionist pedagogical framework in which students are responsible for constructing sharable artifacts (Papert, 1991; Winn, 1993, 1995). For example, students have built VR worlds to represent ecological cycles, developing rich understanding of the various cycles as they do so (Winn, 1995). Our research also uses three-dimensional modeling software to establish an environment in which students take responsibility and ownership for constructing their own, unique three-dimensional worlds.

We have been exploring the potential of desktop three-dimensional modeling tools to actualize abstract facts and concepts as part of local activity (Barab, Hay, Barnett, & Keating, 2000; Hay & Barab, in press-a). In contrast to immersive VR, which places students in the virtual world, we use software that simulates a three-dimensional environment on a two-dimensional screen, providing a window on the world. In these environments, students can develop their own reasoned interpretations as they construct and reflect on their models. For example, undergraduate astronomy students working with three-dimensional modeling construction tools were able to manipulate and examine objects in their virtual solar systems, allowing understanding to emerge from their local experiences (Barab, Hay, Barnett, & Keating, 2000; Barab, Hay, Squire, et al., 2000; Hay, Johnson, Barab, & Barnett, in press). These students were able to enter various coordinates, sizes, rotations, and tilts to explore (and challenge) their conceptions of the solar system, as well as their ability to use mathematical formulas. In this study, we continue to examine the potential of three-dimensional modeling tools in supporting learning by tracing the historical development of the practices of geometric transformation and three-dimensional animation.

LEARNING AS ACTIVITY

At the core of cognitive science and resultant pedagogical models is a Cartesian worldview grounded in mind–matter dualism, which suggests the polarization of the learner and the learning context (Barab et al., 1999; Bredo, 1992; Derry, 1992; Dewey, 1938/1963, 1925/1981; Prawat & Floden, 1994; Shanon, 1988; Swenson, 1997, 1999; Turvey & Shaw, 1995). Such a view has resulted in the separation of learning from doing and the treatment of understanding concepts as somehow independent from practice and from those contexts in which they have functional meaning (J. S. Brown, Collins, & Duguid, 1989; Dewey, 1938/1963; Lave & Wenger, 1991; Resnick, 1987). In schools, concepts are frequently abstracted from those situations in which they are relevant and of value, reified as facts, and treated as self-contained entities. These abstracted descriptions are then imparted to the student from textbooks or the teacher without connection to the communities of practice who value it (e.g., scientists, mathematicians, and journalists), the situations in which it is valued (see Anderson, Reder, & Simon, 1996), or the processes by which they were created (Latour, 1987). In this arrangement, learning activities are organized around domain-level concepts and standards with efficient transmission, as opposed to meaningful participation becoming the focus of the classroom activity (Barab, 1999; Barab & Landa, 1997; Lave & Wenger, 1991).

We believe that the treatment of concepts as disembodied entities separate from practice and particular environments leads to circular relations in which meanings become self-referential; that is, their meaning is dependent on the internal structures and relations among characteristics of the concept itself as opposed to relations with the environmental conditions that the concept was meant to characterize. If the meaning of the concept only refers to itself, then it forms a closed circle, disembodied from the environmental particulars through which the concept gains meaning (Swenson, 1997). It is these types of impoverished, self-referential understandings that the philosopher Alfred Whitehead (1929) described as inert, pertaining to concepts that can be recalled when students are explicitly requested to do so, but not used spontaneously in other situations even when they are relevant. In contrast, we view concepts as intellectual tools that are best understood in terms of the learner practices in which they are actualized and in terms of the intertwined relations among the concept and local environmental conditions. Said succinctly, concepts both constitute and are constituted through situated activity.[1]

In our view, conceptual understandings are best treated, learned, and understood as ways of describing sets of relations among individuals and environments that aid the learner in making sense of the context in which they are functioning—that is, we treat conceptual understanding as a part of activity and not as structures in the mind. In fact, we view knowledge as effective action and believe that its growth is best supported through contexts predicated on participation and not acquisition models of learning (Lave, 1993; Sfard, 1998). Given this commitment, our focus has been on establishing environmental conditions that aid the learner in perceiving, understanding, and creating sets of relations among local environmental particulars. In these learning environments, learners' understanding of the relations among environmental particulars and their evolv-

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[1] We use the term *activity* to refer not to doing a disembodied action, but to doing to transform some object, with a focus on the contextualized activity of the individuals' environment system as a whole (Gibson, 1979; Young & Barab, 1999).

ing conceptual understandings are continually changing through their experience and, in turn, so is their conceptual understanding (Demastes, Good, & Peebles, 1995; Smith, diSessa, & Roschelle, 1993). As part of our project-based framework, learners are continually creating and evolving sets of relations among local environmental particulars through their practices in relation to completing projects. For example, we have been supporting high school and college students in changing the dimensions and sets of relations of the Earth, moon, and sun in three-dimensional models to understand eclipses (Barab, Hay, Barnett, & Keating, 2000); supporting preservice teachers in adding different constraints to their lesson plans as they get feedback from kindergarten through Grade-12 teachers and students (Barab, Squire, & Dueber, 2000); supporting middle school students in working with actual scientists to carry out real-world scientific investigations (Barab & Hay, 2001); and supporting middle school students in developing progressively more detailed representations of gorillas—from video, to pipe-cleaner models, to virtual three-dimensional models of gorillas—to understand gorilla behavior.

An exciting process that occurs when learners are immersed in participatory, as opposed to didactic, learning environments is that conceptual understanding is multigenerational; that is, it evolves and becomes more sophisticated over time through, and as part of, the local activity (Smith et al., 1993). To clarify, we do not dispute that concepts can be taught as self-contained entities or even memorized as facts cleaved from those contexts in which they have value. Rather, our perspective is that these types of impoverished treatments limit learners' conceptual appreciation for the sets of real-world relations that the concept is meant to illuminate. Our commitment as educators is to design and research PLEs in which learners are actively involved in practices that require and support the development of rich conceptual understanding as part of the learner practice. Whereas traditional theories suggest learning is a precursor to activity or that activity (sensory, mental, and physical) is a precursor to learning, our ecological perspective avoids these dualisms by conceptualizing learning as activity and activity as learning (Barab, Barnett, Yamagata-Lynch, Squire, & Keating, in press; Barab et al., 1999). From an ecological perspective, context includes the individual, that which the individual is acting on, and the environment through which these components dynamically interact (Gibson, 1979). Furthermore, from an ecological perspective, any description of learner functioning must account for, at a minimum, individual–environment relations. Learning cannot be separated from this interaction, and instruction, which also cannot be considered in isolation from this interaction, involves supporting learners in orchestrating these relations (Barab, 1999; Young et al., 2000). Our argument is not that concepts do or do not exist, but rather that in authentic contexts and in our rich learning environments, activity and conceptual understanding are so intertwined that it is not useful to try to separate knowing a concept from doing a practice.

These notions are consistent with Dewey's (1938/1963) description of "learning by doing," although we would contend that learning is doing. Treating knowing and doing as inextricably related is also consistent with other terms, such as intelligent action (Ryle, 1949), mind as action (Wertsch, 1998), or Cunningham's (1992) description of the semiotic process. The ideas also bring to the forefront Sfard's (1998) distinction between the acquisition and the participation metaphors. Our focus is on the participation metaphor, with an emphasis on designing contexts that support learning concepts through meaningful trajectories of activity. Consistent with A. L. Brown's (1992) notion of design experiments, we have been designing rich contexts for learning (as opposed to conducting isolated laboratory experiments) and then capturing the learning trajectory so as to document the interrelations of concepts and activity. At times, this has involved designing and researching semester-long courses and, in the case of this article, shorter camps for high school students.

A move toward activity-based theories and away from a representational epistemology is concordant with the works of Dewey (1925/1981), Rorty (1979), and Quine (1969), who rejected the notion of conceptual representation as primary in explaining learning. It is our contention that a full account of activity makes unnecessary an epistemology of representation. The following is from Garrison (1995):

> Once we have a substantial theory of activity and enculturation to learning, then we have no need of an epistemology of conceptual representation. That is precisely why Dewey himself turned away from traditional epistemology toward a philosophy of education. (p. 718)

Such a philosophy dismisses the role of internal representations in learning and emphasizes a change in relations or, more specifically, a change in the individual's position with respect to the trajectory of experience defined by the practices and goals of the particular context. We are developing empirical accounts of participation; providing evidence regarding the unity (not separation) of conceptual understanding and contextualized activity; and resulting in, to borrow a term from Lave and Wenger (1991), the learner or participant becoming *knowledgeably skillful.*

Central to what is meant by the term knowledgeably skillful, and to the ecological theory underlying this work, is an epistemological commitment that conceptual understanding and knowing more generally are acts (e.g., knowing about) and not things (e.g., knowledge; Barab & Duffy, 2000). Knowing about or being knowledgeably skillful refers to relations-making acts that connect individual and context, person and world, and moves beyond the dualisms that Dewey (1938/1963) argued permeate thinking in education and cognitive science more generally. The following is Lave and Wenger's (1991) description:

> Participation … can be neither fully internalized as knowledge structures nor fully externalized as instrumental artifacts or overarching activity structures. Participation is always based on situated negotiation and renegotiation of meaning in the world. This implies that understanding and experience are in constant interaction—indeed, are mutually constitutive. The notion of participation thus dissolves dichotomies between cerebral and embodied activity, between contemplation and involvement, between abstraction and experience: persons, actions, and the world are implicated in all thought, speech, knowing, and learning. (pp. 51–52)

In this study, we attempt to empirically support this intertwining of conceptual understanding and contextualized activity and to capture their mutual coarising.

KNOWLEDGE EMERGENCE, EVOLUTION, AND DIFFUSION

Roth (1995, 1996; Roth & Bowen, 1995) studied the emergence, evolution, and diffusion of knowledge in kindergarten through Grade 12 science classrooms. When Roth (1996) discussed knowledge, he was referring to resources (facts and formal rules, heuristics, and physical objects) and practices (conceptual, material, and social). He used actor–network theory (Latour, 1987) to portray the diffusion of resources and practices in science classes; thus, providing empirical evidence for understanding the distributed and situated nature of learning and knowing in school settings. Actor–network theory is a sociological approach developed by Latour (1987; Callon & Latour, 1981) to trace the historical development of scientific knowledge and artifacts across a society. Roth (1996) adapted this approach for examining the diffusion of knowledge across a classroom community in which students worked collaboratively in a project-based learning environment. In one study, elementary students participating in a 13-week unit on civil engineering were expected to develop a bridge, using toothpicks, that had to have a minimum span of 30 cm (Roth, 1996). Analysis of videotaped classroom interactions and field notes allowed the researchers to trace the diffusion of students' adoption and understanding of resources (facts and objects) and tool- and concept-related practices.

Results suggested that the process of learning a tool-related practice (in this case, the use of glue guns to connect toothpicks) actually transformed the classroom community as the children began to embody the practice. Roth (1996) documented the trajectory of the learner from peripheral participant to core participant—a process that occurred as the individual and the group implemented particular resources and practices. Notably, specific objects (e.g., placing a flag on one's bridge) tended to spread relatively easily and had little effect on the overall composition of the classroom, whereas tool-related practices (e.g., using the glue gun) diffused more slowly and had the greatest impact on the overall composition of the community. In contrast to both of these, the diffusion of intellectual- or concept-related practices (e.g., using triangulation in their projects) was extremely slow and occurred only with constant prompting by the teacher. As opposed to using triangulation in their models as a practice, students were able to express the textbook definition (“triangulating can support structures”) rather quickly, suggesting that in certain learning situations, concepts can remain inert. In Roth’s (1996, pp. 197–198) study, he argued that the student conceptions of triangulation remained inert because they were introduced as a “teacher-desired solution” in response to a teacher curricular objective—rather than emerging from a student-determined need to solve a particular problem.

Although students in Roth’s (1996) study were clearly participating in the practice of building model bridges, there appeared to be a separation between student understanding of a concept (the notion of triangulation) and the carrying out of practices in which conceptual understanding was part of local activity (building bridges that used triangulation as a design principle). Roth (1996) credited this separation between learning the practice and the concept to the fact that within schools, the curriculum frequently directs the process of learning about concepts with an emphasis on, “transmitting legitimized knowledge rather than with participation in practices” (p. 211). As a result, students are no longer in control of their learning, and learning is no longer a natural progression with respect to the completion of a meaningful activity as perceived by the students, leading to the separation of knowing and doing.

In Roth’s (1996) context, available tools (i.e., the glue gun) allowed students to carry out the tool-related practice without developing an appreciation of the sets of relations characterized as triangulation. In fact, the glue gun allowed students to create extremely strong joints with glue rather than by using triangulation. Thus, this tool undermined the teacher’s triangulation objectives by making it possible for students to engage in effective model-building practices without the need for triangulation. In contrast, the goal in our research is to design and study environments in which students are immersed in technology-rich activities that require the application of conceptually rich practices. Although these practices are informed by an understanding of complex relations (e.g., building a three-dimensional model of the solar system), they also inform and evolve these same conceptions through an iterative design process (Lehrer, Horvath, & Schauble, 1994; Stratford, Krajcik, & Soloway, 1998). More specifically, concepts are nested and visualized as part of local activity that involves engaging in particular practices to design and build three-dimensional worlds. It is toward aiding students in grounding understanding across local activity (including student practices and environmental particulars such as textbooks or relations among VR primitives) that we have incorporated three-dimensional modeling technology in the research presented here involving activity groups constructing shared artifacts within a PLE.

METHOD

The primary focus of this study is to describe the development of student understandings and practices within a technology-rich, collaborative PLE. To better understand how learning occurs through participation, we employ naturalistic methods (Guba & Lincoln, 1983; Lincoln & Guba, 1985), building descriptions of the camp experience, and then creating networks of students' trajectory of participation. In this section, we describe the camp, our methods for data collection and coding, and our procedures for constructing networks and selecting tracers.

The Summer Camp

The study took place at a summer camp for high school students held on an urban university campus. Students attending the camp used state-of-the-art VR technologies and software to design VR worlds, eventually to be displayed on the World Wide Web for middle school students to use. A total of 18 students (4 women and 14 men) from 15 high schools signed up to attend the camp for five 6-hr work days and a final presentation day. The students had varying degrees of computer skills, with all students having used computers fairly extensively for at least 2 years. Although students in the camp worked on three different VR projects, in this article we focus on two projects that used similar technologies: a theater project and a solar system project.[2] Each project was assigned an education teacher who was expected to assist the learners in the design of their VR worlds, and a technology teacher who assisted learners in the technological instantiation of these worlds. The two teachers worked with the same group for the entire week. In addition, the camp director, Kenneth E. Hay, designed and developed the camp and occasionally intervened to assist students using the technology or to promote a participatory, nonlecture-based, learning environment.

Students were divided into one of two groups, depending on their interests. Based on initial descriptions of each project and observations occurring over the course of the week, the following descriptions of each group and project are offered:

- Theater group: This group consisted of 5 male high school students with all of the members having previous computer programming experience. Group mem-

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[2] A third group developed a virtual tour of the statehouse. However, these students used different technologies (Apple computers, Quicktake cameras, and various software) making their project significantly different and difficult to compare. Furthermore, students working on this project spent much of their time away from the camp (at the statehouse), which made it difficult to capture much of the interaction and learning that took place.

bers were assigned the task of selecting a play (they chose *The Monkey's Paw*); constructing actors, props, and scenes; animating the scenes; and laying down soundtracks. Specific constraints for the project were left relatively open—learners were encouraged to adapt the play as they saw fit to produce an entertaining experience for the audience. In this way, the teacher encouraged authentic constraints rather than teacher-specified values to constrain the activity. To produce the play, each of the students had a Silicon Graphics computer for their use throughout the week.

•Solar group: This group consisted of 4 male and 1 female high school students with all of the members having previous computer programming experience. Group members were assigned the task of developing a VR, dynamic, interactive, scale model of the solar system. The emphasis in this camp was on creating accurately scaled models of the solar system. In the solar group, primacy was placed on creating models that accurately depicted the planetary dynamics (orbits and rotations) of the solar system. There were four Silicon Graphics computers available for the 5 group members.

The two groups worked in the same room but were physically separated from one another by tables and computers. Posters related to the group's project topic were displayed in each area. Each day, students worked for approximately 3 hr on their projects and then ate lunch as a group while continuing to discuss their projects. Following lunch, students worked for another 4 hr. On Saturday (Day 6), parents and siblings, university personnel, the teachers, and other interested members of the surrounding community were invited to watch each group engage in a 20-min presentation of their project. Saturday's presentation culminated the camp experience and served two educational functions. First, it gave the learners a clear deadline and focus to their projects. Second, it gave the learners a clear audience for their work. They knew that their work would be shown to their families, available on the Web, and used in upcoming camps with sixth-grade students. Learners were also made aware that their models would be used as resources in future science camps for our high school students.

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 kindergarten through Grade-12 students. Three-dimensional modeling tools, in general, and VR editors, in particular, have formed a bridge between the limited technology skills of our students and the processes of computational modeling. Specifically, this technology allows our students to create models to address questions using VR modeling language (VRML), which is a language similar to HTML in that it establishes a common standard for making VR easily distributed over the Internet. During the camp, students used high-end Sili-

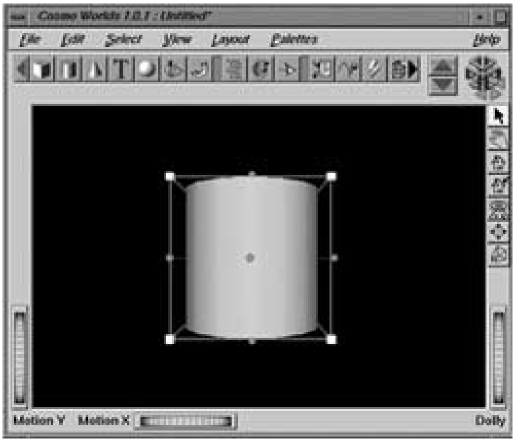

FIGURE 1 Screen shot of a cylinder created in CosmoWorlds, the virtual reality modeling language tool that camp participants used.

con Graphics machines with a VRML editor installed[3]—the latter providing a multifunctional tool for creating, manipulating, texturing, and animating shapes; grouping and ungrouping objects; creating various viewpoints from which to view VR worlds; and adding or modifing 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. Whereas adding color or positioning the object anywhere in the three-dimensional space would take multiple lines of code, this procedure takes the user of an editor only a few clicks and drags (see Figure 1). These direct manipulation editors afford students the opportunity to quickly develop a dynamic three-dimensional model as part of an inquiry process.

Data Collection

Naturalistic inquiry involving qualitative data was used to gain a holistic vision of the week-long VR camp (Guba & Lincoln, 1983; Scriven, 1983; Stake, 1983). An evaluator was present for all 5 days of the camp and for the final presentation day. Throughout the camp, the evaluator maintained field notes based on observations; participated in nightly debriefing sessions with one of the camp directors (Kenneth

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[3] At the time of the camp, CosmoWorlds was prereleased and available only for Silicon Graphics machines. Subsequently, it was released for standard desktop personal computers. Currently, we are using a free version of Virtual Reality Creator (another virtual reality modeling language editor), on basic personal computers, and in one middle school, we are using the software on laptops.

E. Hay); and conducted interviews with students, course teachers, and both directors. Whereas Kenneth E. Hay was a participant observer, the primary evaluator (Sasha A. Barab) was not involved in the design or the ongoing activities of the camp. Data were also collected with four video cameras and tape recorders: One pair was directed at each of the two groups, and a roving camera and tape recorder were directed at "interesting" events, people, and objects. There were a total of ten 2-hr videotapes for each group.

In nightly meetings between the two researchers (the outside evaluator and the camp director), field notes, student interviews, and observations were discussed to generate assertions used to direct data collection efforts the following day. Consistent with Roth's (1996) previous work, we collected data that (a) documented practices (e.g., tool use, problem solving, and student inquiry) and resources (e.g., concepts implemented and tools); (b) captured the discussions among students and among students and teachers; (c) documented the progress of student projects; (d) followed 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 understanding evolved over time.

Data Coding

Barab, Hay, and Yamagata-Lynch (in press) developed an approach of constructing networks of action-relevant episodes (CN-ARE) for identifying important interactions and building activity networks to represent the historical development of select phenomenon (e.g., the practice of animating objects or emerging features of student-created models). These networks, composed of nodes and links, characterize the interactions related to the phenomena being investigated. Data coding was done by two researchers who were involved in data collection and by two doctoral students who joined the research team after the camp was completed, and who relied on the examination of videotapes, completed projects, and field notes to build their interpretations.

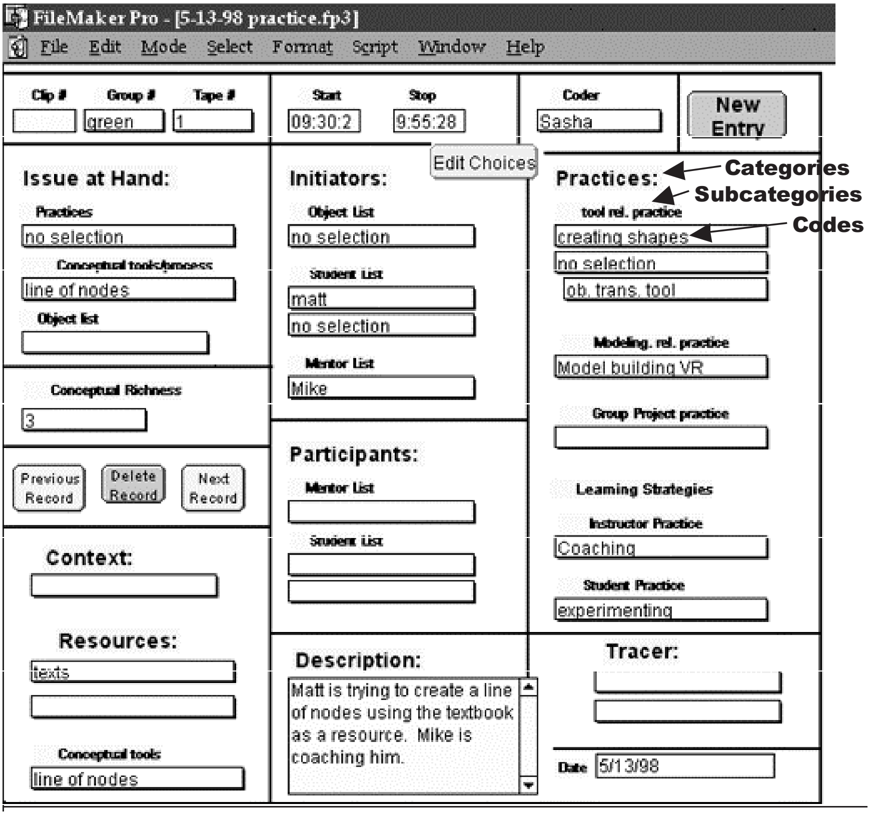
Using the CN-ARE methodology, data analysis involved first videotaping all interactions and then examining videos, "chunking" the data into discernible units of analysis that are referred to as nodes. The size of the unit of analysis comprising a node is idiosyncratic to the researcher's goals: Some researchers want more macrobrush strokes, whereas others are more concerned with a fine-grain analysis. The focus in this study was to define the constitutive elements of an episode (node) and then parse up our observations into component episodes. In our description, an episode minimally contains information about the issue at hand (theme), who the initiators are, who the participants are, what practices the initiators are engaged in, and what resources are being used (see Table 1). Each of these categories may also

TABLE 1
Summary Labels for the Various Features that Constitute a Node

Category	*Description*
Issue at hand	A summary label that is chosen to identify the content of the node. It is the direct object of discussion or manipulation (the only way a practice can be considered an issue at hand is if it becomes the explicit object of discussion or manipulation). It can refer to an artifact, tool-related practice, or a conceptual tool–process.
Initiator	An individual or group (when engaged in a practice as a single unit) that is producing an action. Although we listed only observable initiators, it is important to note that actors do not emerge in a vacuum; rather, they exist within a context that is reciprocally constituted by the cultural surround and transformed by their initiator actions. In this fashion, the cultural surround could arguably be considered an initiator involved in defining the specifics of the issue at hand. However, it becomes impossible and, we believe, overly presumptuous to define the numerous aspects of cultural influence that interact with the issue at hand. Therefore, we have not included these nonobservable (yet potentially important) factors in our coding scheme and must acknowledge this as a limitation. We have also not included nonhuman objects, such as computers; instead, the contribution of these objects to the historical development of an particular tracer is captured as part of the network as a resource or tool.
Participant	An individual who is involved in a node but not initiating the action.
Practice	An activity that is carried out by an initiator who is using a resource. Practices can be tool related (e.g., embodied tool-related laboratory skills), scientific (e.g., calculating), instructional related (e.g., coaching), learning related (e.g., using an inquiry strategy), or conceptual (e.g., theorizing about quantum mechanics), and always involve the use of a resource.
Resource	"any piece of information, object, tool, or machine" that an initiator uses to carry out a practice (Roth, 1996, p. 191). In addition to technological tools, our definition includes those of a conceptual nature (e.g., heat–color relations) and those of a more social nature (community norms). An artifact is transformed to a resource when it is used by an actor as part of a practice.

have subcategories; for example, under "practices," we additionally delineate between those that are teacher-related, student-related, tool-related, and modeling-related practices. Each of the five broad categories and any subcategories then contain specific category types; for example, under instructional practices, we included coaching, Socratic questioning, lecturing, and just-in-time lecturing, among others. When a change occurred in practices (the issue at hand or who the initiators were), we coded the node as a new event.

The sets of subcategories and category types are created using the constant comparison method (Glaser & Strauss, 1967), and they occur through an iterative process involving extended group discussions. Through these discussions, data and emergent interpretations interact in a dialectic fashion, reciprocally informing and being informed by the other (Lather, 1986), allowing us to develop grounded categories and codes (Glaser & Strauss, 1967). To aid the coding process, a com-



Clip #:
Group #: green
Tape #: 1
Start: 09:30:2
Stop: 9:55:28
Coder: Sasha

Issue at Hand:
Practices: no selection
Conceptual tools/process: line of nodes
Object list:

Conceptual Richness: 3

Context:

Resources:
texts

Conceptual tools: line of nodes

Initiators:
Object List: no selection
Student List: matt
no selection
Mentor List: Mike

Participants:
Mentor List:
Student list:

Description:
Matt is trying to create a line of nodes using the textbook as a resource. Mike is coaching him.

Practices:
tool rel. practice: creating shapes
no selection
ob. trans. tool
Modeling. rel. practice: Model building VR
Group Project practice:
Learning Strategies
Instructor Practice: Coaching
Student Practice: experimenting

Tracer:

Date: 5/13/98

FIGURE 2 Web-based coding form used to capture the salient information of a node.

puterized coding form was developed with a relational database that allowed the researchers to input the basic information (e.g., time, date, coder, tape, etc.); a rating of the conceptual richness; any other ethnographic field notes; and to code the issue at hand, initiators, participants, resources, and practices for each node (see Figure 2).

For the 1-week summer camp, this coding process resulted in a database containing 480 nodes, with 238 for the solar group and 242 for the theater group. In establishing reliability for our methodology, two researchers coded the same 60-min segment separately. Results indicate 88% agreement in terms of number of nodes selected, with one researcher selecting 22 episodes to be categorized as nodes and the other selecting 25 episodes. Examination of the videotapes and the selected nodes suggest that of those 22 nodes, all but 1 corresponded to the same segment in the video. The next step in establishing reliability of the coding scheme involved examining the categories, subcategories, and codes selected for each node. On average, both coders selected eight categories (pull-down menus) per node (e.g., one issue at hand, two initiators, one participant, two practices, and two resources). In terms of the content selected within a category, there was 80% agreement.

Although training two researchers to code segments with consistency is important, the trustworthiness of a coding scheme based on our subjective interpretations of such complex events is certainly not a straightforward process (Lincoln & Guba, 1985). We have to coordinate student gestures, dialogue, computer screens, and a class history all into a momentary judgment that occurs within the continuous flow of data. Although later we can revisit videotaped episodes, it is not possible to capture all the information in one video screen or to resituate oneself into the momentary contextual dynamics based on a video. Even if we could, the situation for the researcher may be very different than the situation for the learner, and, as such, any interpretive judgments are necessarily suspect. However, despite these concerns, we found the coding scheme to be useful here, and in previous work, for generating an inscription that can scaffold the researcher's interpretation and presentation of the historical development and diffusion of the tracer of interest (Barab, Hay, & Yamagata-Lynch, in press). For this study, we used the database to build case descriptions, examine the frequency of particular practices, and build networks of activity for describing the historical development of two practices and nested concepts. Using grounded theory methods (e.g., saturation, theoretical sampling, checking conditions across cases, and the constant comparative method), we will continue to build evidence on the credibility and trustworthiness of our coding scheme in future work.

Network Construction

We selected two conceptually rich practices, animation and geometric transformation, to serve as tracers from which to build a network to trace their historical development over time (Newman, Griffin, & Cole, 1989; Roth & Roychoudhury, 1993). Whereas Newman et al. used the term tracers to denote a preexisting methodological strategy to find the same activity across different contexts without resorting to intensive interpretation, in our approach, tracers emerged from the data through grounded theory development. In addition, we did not select the same tracer for each project, but instead selected two different tracers that were central to the activities of each group.

In building these networks, we used the CN-ARE methodology (Barab, Hay, & Yamagata-Lynch, in press), and we drew on the rich database of 480 nodes discussed earlier. Once the videotapes were coded and the database generated, the CN-ARE methodology involved selecting the phenomenon of interest, the tracer, and following its history by using the database to build a network consisting of various nodes

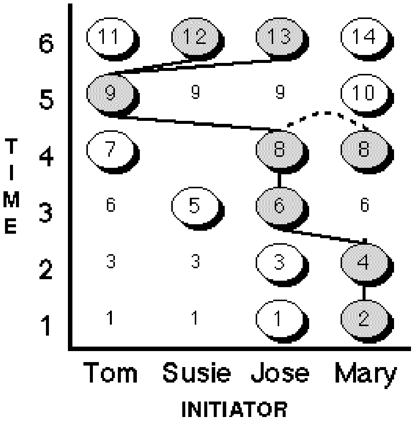


FIGURE 3 Numbered circles represent node initiators and noncircled numbers represent node participants. Shaded nodes represent those nodes in which a particular practice is being carried out, referred to here as *the practice.* In addition, lines represent links between two nodes, with the dashed line representing nodes that were dually initiated. Links are drawn when two nodes share a common practice or issue at hand and are related historically through a common initiator.

(the action-relevant episodes) and links (connections among the nodes). This connection of nodes and links represents the historical development of the tracer (see Figure 3 for a network taken from Barab, Hay, & Yamagata-Lynch, in press). Figure 3 illustrates a hypothetical network of a tracer with links representing the connection of two nodes that share common practices or the issue at hand and are related historically through a common actor. In this network, all the shaded nodes in Figure 3 are related to a particular tracer—referred to as “the practice.” We present this vignette simply to illuminate how to interpret the final networks of action-relevant episodes.

In this hypothetical vignette, Mary is working by herself on the practice in Nodes 2 and 4, and the other students are working during this time in a group initiated by José on activities not coded as related to the practice. In Node 6, José calls Mary over to show him and Tom how to do the practice. José and Mary continue by dually initiating a discussion of the practice in Node 8. Then, in Node 9, Tom goes back to his computer and finishes up a prior activity before he asks José to help him (Node 10); Susie tags along. Susie then returns to her computer to work on the practice (Node 12) as does José (Node 13). Last, Mary returns to her computer to work on other parts of the project (Node 14), as does Tom (Node 11). An examination of this inscription provides insight into when individuals participated, with whom they collaborated, and in what role. Examination of the figure further reveals which individuals took the most active role in initiating interactions and in which nodes the practice was being carried out.

Selecting Tracers

Based on our observations, field notes, video analysis, the coding process, and network construction, we selected one tracer for each camp that was central to the camp's activities. In doing so, we looked for tracers that were multigenerational; that is, tracers comprising rich activity that evolved throughout the camp affording a useful window into the emergence, evolution, and diffusion of knowledge throughout the camp. Useful tracers have a rich history: spanning over multiple time frames and distributed across multiple members. In this way, we hoped to capture the student practices that constitute understanding, and in doing so, develop a picture of the coemergence of conceptual understanding and learner practices in situ. Specifically, we selected animation and geometric transformation as two network tracers that provide a means of examining how knowledge emerged, evolved, and diffused throughout the camp. Because our observations of students' understanding of animation and geometric transformation were so intertwined with the contextualized activities learners were carrying out, we refer to these as practices rather than concepts.

Our criteria for selecting the tracers were that (a) they had a rich history, spanning over multiple time frames and distributed across multiple members; (b) they were illuminative of the themes that we identified as central to camp activity; and (c) there were video data on a large percentage of the interactions related to their trajectories. As such, tracers were chosen to be illuminative examples that help tell the story of the camp, rather than comprehensive tracers that represent the full camp experience, or exemplars that serve to promote the camp activity. In presenting these tracers, we highlight only those nodes that directly relate to the two tracers of interest. As such, we only present the highlighted nodes—those that are directly related to either the animation or the geometric transformation practice.

RESULTS

We present our results in three sections. The first section presents the data associated with the solar system camp. We begin by drawing on our observations, field notes, student–teacher interviews, videotapes, texts, student-developed artifacts, and the database of nodes to build an account of the solar group so as to contextualize the reader. Next, we trace the historical development of the geometric transformation practice to examine the historical development of a particular practice in greater depth. In the second section, we shift our focus to the theater group, which, like the solar group, begins with a general narrative account of the group followed by the historical development of a key practice (i.e., animation). A key feature of the analysis of both practice tracers is an explicit focus on the inextricable relations of practices and conceptual understandings with both constituting and being constituted by the other. Last, having presented an overview of the cases and the tracings of student practices, we present a cross-case comparison that highlights two themes characterizing group dynamics (Merriam, 1998).

Solar Group

Over the week, the group members worked in dyads to create a series of virtual models of both the inner and the outer planets, with different students responsible for different planets (see Figure 4 for a two-dimensional, static snapshot of a student model). These models were then combined on the final day of the camp. The models incorporated numerous astronomy concepts and phenomenon, such as relative scale, eclipses, equinoxes, orbital tilts, and all the planets, as well as a subset of planetary moons. The central challenge, as perceived by the students, was to represent relative scale of the solar system on a 20-in. monitor so that realism was maintained and the final product was still visually appealing. Although each student constructed models of complex astronomical phenomena, time constraints prevented students and teachers from combining these separate pieces into one complete project. Furthermore, students frequently appeared confused and had difficulty mastering both the astronomy content and the software. Despite these difficulties, students worked hard and showed pride in their presentations and work.

The first day of the camp opened with the teacher introducing the project. She led the five-member group through a discussion of what data they needed to create a model of the solar system. Group members participated sparingly, with the teacher asking all of the questions, supplying most of the answers, and transcribing important points on the board. The teacher also identified most of the potential resources and divided the roles and tasks in the group. After this 1-hr introduction, group members scoured the Web for additional astronomy-related resources.The teacher con-

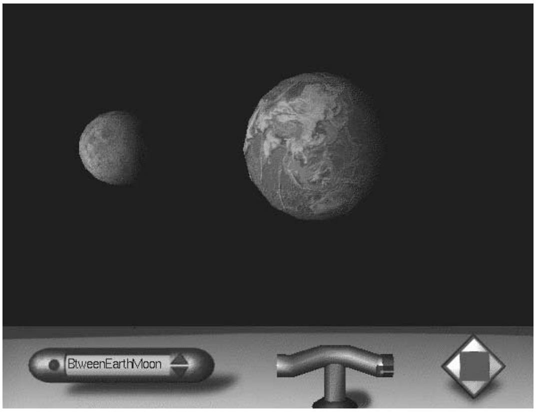


FIGURE 4 Screen shot of an eclipse created by the solar group.

tinually challenged the learners to consider how they would convert their data into usable information and how they could model the vast distances of the solar system. In this way, she defined the key challenges of the project for the group, rather than allowing the group to identify the struggles inherent to the activity.

Midway through the first day, the technology expert demonstrated how to use CosmoWorlds, the VR creation software that we used during the camp. He gave a 20-min demonstration that left students visibly bored. Finally, over 2 hr into the session, the group began to construct their model solar system. Quickly, the group encountered problems with CosmoWorlds: They created and lost planets and could not navigate in three-dimensional space. Perhaps not surprisingly, the group members appeared frustrated with the process. Little progress was made, and the teacher called the group back together to refocus them on modeling questions. Students were reluctant to give up working on their models to give their attention to the teacher, requiring her to make repeated requests for their attention. Once the instructor finally gained the students' attention, she was unable to elicit any responses from them describing what they were trying to accomplish or why. At the end of the day, the technology coordinator gave 1 student a just-in-time tutorial on how to create viewpoints in their model. This knowledge spread quickly throughout the group, and the first day ended with a flourish of productive activity.

On the second day, the technology coordinator led class, walking the group through specific CosmoWorlds functions. As on the first day, the group members were visibly bored. After 30 min, the students separated and constructed individual models of the planets. After 1 hr of struggling with the notion of relative scale, the camp director intervened and explained the challenge of sizing planets conceptually and then gave a brief discussion of how to use the level of detail (LOD) function on the tool. The students latched on to this tool-related practice, quickly transcended the technology teacher's understanding, and eventually explained the process to the technology teacher who did not completely understand how to use multiple levels of detail to fit multiple sizes and scales on the screen at once. The students then continued to proceed to work on their own, with coaching, resulting in a productive last ½ hr of the session.

The third day picked up where the second day left off, with groups working collaboratively with the support of the camp director. As the camp director divested himself from the group, the teacher appeared concerned that the students were not learning, and she struggled to reassert herself by delegating tasks, directing activity, or even taking control of students' mice. Again, students appeared more interested in working on the computer than conforming to the teacher's agenda, with one student commenting, "God, I wish she would let us work." This pattern was exacerbated on the third day when the teacher gave a lecture on orbits and made a table of the planetary data that denied students the powerful opportunity to create inscriptions to guide their work (Roth & Bowen, 1995). By the fourth day, the teacher became visibly frustrated and began withdrawing herself from the project.

Students seized this opportunity to direct the project, working collaboratively, but independently, from the teacher. The technology coordinator began playing a Socratic, facilitative role, questioning students and challenging their thinking. Students also recustomized the table of planetary data based on the scales they chose to use in building their model, and they added in viewpoints to their model. Viewpoints refer to perspectives or "camera positions" that can be placed in a three-dimensional model, allowing viewers of the model to immediately shift to various locations and examine the model from the new perspective; for example, standing on the moon and looking at the Earth.

The week ended with the technology coordinator showing students how to view their projects on the Web, which energized the group and renewed their interest in perfecting their projects by the camp's deadline. In achieving this end, they delegated project tasks according to each member's strengths. Despite the challenges earlier in the week, the group completed a model of the solar system that all students stated met their expectations. In contrast, one of the camp directors stated during interviews that the final products had not met his initial expectations; he had hoped to see more dynamic and comprehensive final models.

Geometric transformation tracer. Although each tracer is nested within the fully developed network of camp activities, for space reasons we present here only the nodes directly related to either the animation or the geometric transformation practice. Geometric transformation serves as our primary practice tracer for the solar group. Roughly speaking, the practice refers to the rendering of the objects in the model so that they are proportional in terms of their relative sizes and distances to those numbers scientists use when describing the actual solar system. However, in contrast to mechanistic descriptions, the practice is complex, and its actualization in situ spans multiple nested practices that require appreciation of important astronomical concepts. We trace a particular set of geometric transformations as they are associated with sizing and positioning planets in the solar group. The power of this main tracer is actually a product of a particular resource (i.e., table of planetary physical data) and another practice from the domain of mathematics (i.e., calculating relative scale). We begin with two component tracers.

This first component tracer is the resource of a textbook—more precisely an astronomy textbook's table of planetary physical data. This table has the planetary size, distance from the sun, and a number of other facts not relevant to the subject at hand. The data on the planet's size and distance are easily found as fact-based knowledge, to use Bloom's (1956) vernacular. These numbers are extremely large and difficult to conceptualize, given that students did not have direct experience with artifacts of this size or work in these large scales. Students used the textbook as a resource for their work; that is, they had a goal (build a model Earth), determined what they needed (how big is Earth?), found a resource that would meet that need (table of planetary physical data), and then found the specific fact they needed (Earth is 12,756 km in diameter). This table of planetary physical data resource tracer, thus, constitutes one of the components of the geometric transformation practice tracer. The second component tracer is creating a relative scale for their solar system. Calculating relative scale (using the table of planetary physical data) involves mathematically transforming a planet's size and distance from the Earth into a set of scaled numbers that learners identify as appropriate for their three-dimensional model.

The table of planetary physical data was first introduced by the teachers at the end of Day 1 as a resource for students. We have found that having an inscription to scaffold our interpretations and descriptions of a network is useful in illuminating the historical development of the tracer and, therefore, included the network in this article for the reader (see Figure 5). The introduction of the table of planetary physical data by the teachers is captured as Nodes 1 through 4 of the activity network that represents the geometric transformation tracer (see Figure 5). The students did not use this table until Day 2 when, for example, Bill (Node 5) and Jake (Node 6) were attempting to create VR objects in their models. Using the table of planetary physical data resource as the basis for their model, they eventually came together and worked collaboratively on Jake's computer (Node 7). It is important to note that at this point, the teachers did some coaching but mostly took control of the process, transforming the data themselves and handing the numbers that were appropriate to build a VR model to the students.

The planet sizes constituted the first conceptual challenge confronting the group in terms of this practice. Sophie and Jason began with the creation of a sphere (Node 8), eventually put a texture[4] on it (Node 9), and then sized it with the direct manipulation tool (CosmoWorlds allows the user to click and drag handlebars to increase the size of the planets; Node 10). This activity provided insight into their alternative conceptions on the relative size of the planets in that they were able to easily see, or not to see, all these planets on one screen. They then used the transformed data table that they had developed under the control of the teachers.

When they used the transformed data table, they had a number of interesting reactions. For example, Sophie and Jason created the sun, Earth, Jupiter, and moon, and then placed them next to each other (Node 11). When they entered the transformed numbers for the Earth, moon, and Jupiter, they were given immediate feedback on the relative size of these heavenly bodies (Node 12). However, when they entered the numeric data on the sun, there was a problem. Actually, there were two problems. First, the Earth, moon, and Jupiter were no longer visible on their screen. Second, their entire virtual world appeared gray in color (Node 13). With

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[4] A *texture* is a two-dimensional image that is stretched over a three-dimensional surface in this software. The students used two-dimensional Mercator geographic maps, NASA composition photographs, and artistic renderings of planets as textures.

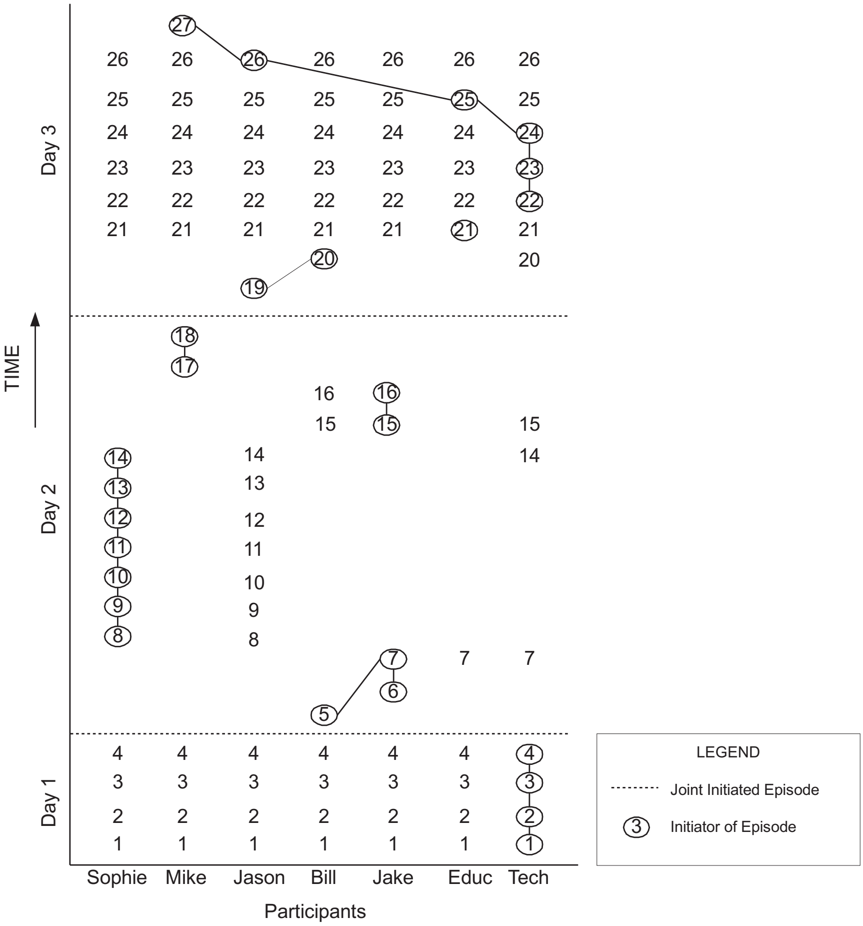

FIGURE 5 The geometric transformation tracer network, showing the geometric transformation-related nodes and links. Nodes are presented for each initiator with numbered circles representing node initiators and noncircled numbers representing node participants. In addition, lines represent observed links between two nodes, with the dashed line representing nodes that were dually initiated.

some prompting by the technology teacher, they used a dolly control in CosmoWorlds to zoom out and then zoomed out some more (Node 14). Finally, they reached a point in which they saw nothing but yellow. They zoomed out some more until they saw the entire sun and no planets. What had happened? The size of the sun was so large, compared to the other bodies, that it had engulfed the other planets and Sophie's original viewpoint as well. It was not until they reoriented themselves that they were able to see both the sun and also reposition the bodies to see the huge differences in the sizes. Sophie exclaimed, “Wow, I never realized … it [the sun] is so big compared to the others [planets].” This event directly and meaningfully confronted her conception of the relative sizes of the planets.

The second conceptual difficulty developed when the other group of students went to place the planets in relative distance to the sun. Using the transformed data, Bill and Jake entered the numeric data into CosmoWorlds (Node 15). Once again, there was a visceral response to what happened. They had their sun and planets created and sized, and then they started to enter in the distances. First attempts led to a state of confusion, with Jake stating (Node 16), “What happened to my planet?” After pulling back their viewpoint, the students confronted their conception on the relative distances between the planets. A similar confrontation led Mike to ask (Node 17), “How can we get the Earth and Jupiter’s orbit on one screen and be real like?” When he later consulted a textbook resource, he came to the following conclusion about how the solar system was illustrated: “This picture is wrong, there is no way they could get Mercury, Earth, and Saturn all in the same picture. The distances are too great … . My science book lied” (Node 18).

Although prior to developing the simulation students were able to quickly find the numbers from the book and even transform them into scaled values, in a real sense they did not understand them. Otherwise, they would have realized that the textbook representation was inaccurate. These misunderstandings about size and distance are not only pervasive, but they are also supported by the standard textbook and movie depictions of the solar system (see Pfundt & Duit, 1998; Wandersee, Mintzes, & Novak, 1994, for a review of research on alternative conceptions in science). Only when they created their own solar system with real data did they come to appreciate the magnitude of these differences. This was apparent on Day 3 when Jason stated (Node 19), “I never realized how big the sun was or how large the solar system was.”

It is interesting to note that the tracer did not end here. This new understanding created new and interesting problems for learners, as articulated by Jake who asked the technology teacher (Node 20), “How are we going to possibly model it realistically?” Learners became engaged in the conceptually rich problem that required them to grapple with the nested issue of limiting agents (constraints)—an important consideration when designing models of complex phenomena. For example, apperception can be characterized as a limiting agent because when the planets are all modeled with the same size and distance scale, it becomes impossible to zoom out to a position to see the entire solar system. Because the planets are too small to see, students as a group, under the guidance of the education teacher, grappled with the issue of developing a realistic model as opposed to developing one that was visually appealing (Node 21). Furthermore, through this struggle for a solution, a new practice or conceptual understanding emerged: LOD. LOD is a VR programming technique that minimizes the computer’s computational load by calculating and displaying only those details that the viewer of the VR world can per-

FIGURE 6 Screen shot of the set created by the theater group.

ceive—not calculating those which are too small or distant to be perceived by the viewer. Operationally, a user far away from a VR object sees a coarse-grained object; as the user moves in closer, the object is replaced with a more detailed object.

Group discussions and just-in-time lectures on LOD were initially about the concept itself and were targeted toward supporting students in developing an appreciation of the abstract concept (Nodes 22–24). At the end of the lecture by the technology teacher, all students except Jason and Mike stated that they did not understand it (Node 25). Jason actually described how this concept would be useful in their models (Node 26): “We could use it in our models to show different stuff as the user moved closer or further away.” Mike, also understanding it, responded (Node 27), “It is cool, but how do we do it?” The students then spent the rest of Day 3 and the beginning of Day 4 applying the LOD concept to their models (Nodes 28–43 are not included in Figure 5 for space reasons). They created a model that included enough details with respect to the Earth, moon, and sun so that their models looked realistic at large distances (e.g., very few features and no moon) and at small distances (e.g., landmasses and a visible moon). Student understanding of LOD emerged within and as part of their local concrete activities as they collaborated with their peers.

The Theater Group

The week began with the teacher setting up the task. The group was to adapt a play for a three-dimensional environment for an audience of middle school students (see Figure 6 for a screen shot of the virtual play). They began by reading several plays, eventually deciding to adapt *The Monkey’s Paw*—a play about a magical monkey’s paw that grants its owner five wishes. Next, the team explored the parameters of the activity and decided to adapt the play as they saw fit. Initially, they were concerned about how to make the play interactive and entertaining for middle school students. Students had many questions for the teachers, particularly concerning the capabilities and limitations of CosmoWorlds. They were actively engaged in the conversation from the beginning, pushing the teacher to define the boundaries of the activity.

Next, students defined what types of props, sets, and characters they would need. In particular, they were concerned with how characters would be animated. Following the teacher's suggestion, students searched the Web for information on the play, resources, and ideas about what animations to include. Students accessed the CosmoWorlds tutorials and quickly taught themselves how to add textures to objects. The group worked through CosmoWorlds collaboratively, assisting each other in learning to use the technology. By the end of the first day, the group learned to create, resize, rotate, texture, and manipulate objects.

The second day began with a brief recap of what the team had accomplished and what their goals for the day should be. The teacher facilitated this discussion, with students contributing significantly. For the second hour, the group members worked relatively independent of the instructor to build props, collaborating when a group member had difficulty with CosmoWorlds. For example, when one student (Ross) had trouble animating, another student (Ted) leaned over to show him how to animate the object, and a third student (Sam) then looked over their shoulders. This type of collaborative learning continued throughout the camp.

In the second half of Day 2, one student began exploring Web sites containing predeveloped three-dimensional characters, which had a profound effect on individual activity as well as the overall classroom community. For example, Ted spent approximately 2 hr creating a door, fully adorned with hinges, trim work, and a knob. On the second day, Ted and his practices were representative of exemplar behavior and central to the formation of the practices that constituted the group's activities. However, when students examined potential objects to be downloaded from a Web resource site onto their computers, they found a more ornate door that was superior to Ted's from an aesthetic standpoint. At this stage in the camp, it appeared that the predeveloped technological artifact (i.e., the door) made Ted's hours of work related to position, sizing, shaping, and so forth, obsolete. Although Ted agreed that the door looked better, he was visually dejected—his head sagged and he used a despondent tone. Furthermore, the group decision to use a predeveloped door relegated the practice of artifact development (and Ted's status within the group) as potentially less important than artifact finding (i.e., Web searching).[5]

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[5] Another perspective on Ted's experience concerns the trajectory of mastery of the complex virtual reality domain. Certain features of the domain (e.g., animation and practices) are functionally more central than others (e.g., artifact search). Ted's initial activity was geared toward mastery of the domain, as well as to direct participation. However, the two are interlinked in practice, and he may have used his time differently had he known about preproduced artifacts.

After much discussion and exploration, the technology teacher informed the group that the student-developed door, which consisted of multiple children already defined, would be simpler to animate through the various functions necessary for the play. Understanding this comment requires an appreciation of parent–child relationships—how subordinate parts (children) are associated with a superordinate object (parent). For example, a hand can be the collection of four fingers, a thumb, and a palm. The hand is the parent and the fingers, thumb, and palm are the children. Likewise, the hand, forearm, and upper arm can be children grouped together to form the parent arm. To make a person shake hands with another person, for example, the parent object (the person) must be separated into its component children (e.g., biceps, forearm, and hand) so that each of these parts can be animated independently. Because the predeveloped artifact was not separated out in terms of its component parts, it was useful only if students limited their perspective on what they wanted to accomplish with the door—that is, if they did not want to open the door. As a result, Ted's ability to build artifacts again became central to the community. The teacher intervened, however, to remind the group not to become too caught up in creating objects, to use time allocation strategies, and to develop a plan for completing the tasks critical for finishing the play. The group took this opportunity to share knowledge about animating in CosmoWorlds. The remainder of the day was spent working in a fluid collaboration, as students worked both independently and collaboratively.

The third day opened with a group discussion of animation. The teacher expressed concern that the team was becoming too bogged down with details and was not going to finish the play. He stated to the group that their play needed to have not only a good set, but good dialogue and refined blocking to be appealing to an audience. The teacher proposed that they next write a script and then determine what scenes they would need. The students responded by sharing their own strengths and weaknesses and by negotiating their roles and responsibilities. As opposed to an earlier discussion, when the teacher recorded all of the notes, a student (Dan) wrote the groups' notes on a whiteboard. The group then stopped model building and recorded voice overs for the play.

On finishing the voice overs, the group recognized that they still needed to obtain a large number of objects for the play in a short amount of time, so they began searching a CD-ROM containing predeveloped objects that could easily be ungrouped and incorporated into the student's three-dimensional world. Here, they found another door that was fully editable and, the group decided, more aesthetically pleasing than the door Ted had developed. In contrast to the door they previously found on the Internet, the object on the CD-ROM could be easily ungrouped and was therefore totally editable. Again, it appeared that the technological development (i.e., a CD-ROM containing multiple objects) would undermine the common labor of the community. However, as it turned out, the available funds only allowed the group to purchase a limited number of VRML objects, and the more elaborate door was not included in the basic purchase. Therefore, financial considerations (an authentic task constraint) limited the breadth to which the reach of this technological advancement would extend. More important, Ted's identity as the core participant, boosted through his skills in carrying out practices central to the success of the group, was again primary. The group finished the day working collaboratively on animations and voice overs with the teacher reminding them to make good use of their time.

The fourth day opened with a quick planning session, and then the team split up to resume animating objects. By this point, they could view their play on the Web and were able to hear their voice overs and watch their animations. They began emphasizing refinements, such as adding facial features to characters. By the second half of the day, they were actually putting scenes together and assembling their independently created objects. With the end now in sight, the team gathered to discuss what remaining tasks they needed to accomplish with the teacher reminding them that it was up to them to determine the level of quality they wanted to pursue. The students affirmed their commitment to create a quality product and decided to focus their remaining efforts on refining animations and creating only those additional animations that were central to the plot of the play. The teacher suggested that they create viewpoints to place viewers in the best position to appreciate the play and to hide any unfinished characters or animations. The day ended with considerable stress, as assembling the final projects revealed problems in the product. Some objects were created in a way that made them nonanimation-friendly, other objects were created out of scale, and not all of the animations ported well to the Internet. By the end of the final day, however, the group settled on a reasonable set of compromises and delivered a product meeting their expectations and most of those held by the camp directors.

Animation tracer. The three-dimensional modeling practice of animation was chosen as an example of how tool-related practices emerged, evolved, and diffused in response to task constraints and student (not teacher) needs for the theater group. Nested within the practice of animation is the practice of creating parent–child relationships, which demonstrates how the understanding of concepts was situated across student interactions with the technology and each other, and it illuminates the reciprocal relations of practices and conceptual understanding.

Within the theater group, animation had a rich network: It was influenced contextually, both in terms of the students performing the animation and the day of the week in which the animation was occurring (see Figure 7). Animation was introduced on Day 1 (see Nodes 1–4 of Figure 7) when the teachers pointed students toward a Web-based tutorial in CosmoWorlds. However, at the end of Day 1, only 2 students, Ted and Zak, had actually used the practice of animation (Nodes 5 and 6). The practice, at this juncture, was appropriated with little personal transformation; that is, Ted and Zak were simply implementing the steps listed in a Web-based tu-

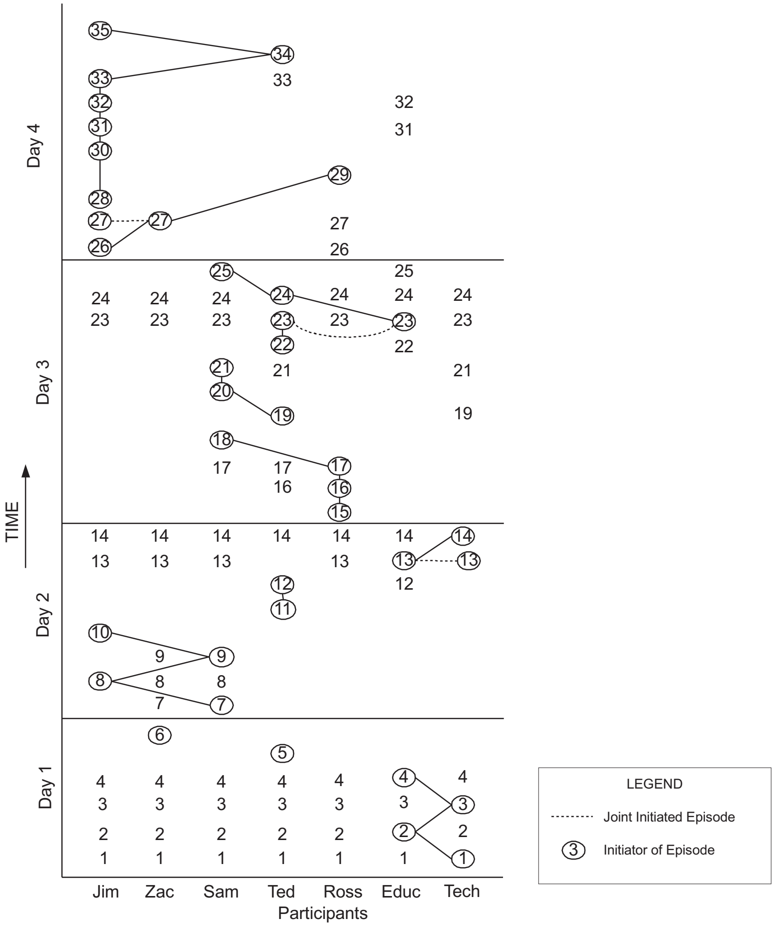

FIGURE 7 The animation tracer network, showing the animation-related nodes and links. Nodes are presented for each initiator with numbered circles representing node initiators and noncircled numbers representing node participants. In addition, lines represent observed links between two nodes, with the dashed line representing nodes that were dually initiated.

torial that was identified by the teachers (Nodes 1–4). However, on Day 2, when another student, Sam, was having difficulty producing a project-based animation, he requested Zak's help (Node 7). Later that same day, another student, Jim, also requested Zak's help but quickly came to an impasse that Zak had not yet experienced (Node 8). Sam, overhearing the discussion between Zak and Jim, showed Zak how to produce the desired effect (Node 9), after which Zak then shared this with Jim (Node 10).

At this point, animation became more complex; students wanted to move one part of an object (e.g., an arm) while keeping another part still (e.g., the body). As a result, students had to develop an appreciation of parent–child relationships, incorporating this notion as part of the animation practice. Here, we continue through our animation network (Figure 7) by tracing the interactions related to the practice or concept of parent–child relationships. Parent–child relationships were used as conceptual tools as part of the practice of animation and were also present in object creation and texturing. Students' introduction to parent–child relationships first occurred at the end of Day 2 when Ted was working with the key-frame animator tool in an attempt to make one of the characters of the play walk across the screen (Node 11). Ted was working with a figure he had downloaded from the Web. The figure was grouped, having only one level with no children, so the first step was to ungroup all the children parts (i.e., fingers, forearms, eyes, feet, etc.) of the parent object (the body). In response to this need, Ted asked the education teacher how to make only one part of his figure move (Node 12). The two teachers then presented a just-in-time lecture about parent–child relationships to the entire group (Node 13). Following this just-in-time lecture, the technology teacher coached Ted through the procedure for ungrouping his object, while the rest of the group watched (Node 14). Although the other students were not working on parent–child relationships, for Ted, the introduction to parent–child relationships was grounded within a concrete experience and an immediate need that he appeared to value.

The following day, Ross needed to ungroup the monkey's paw so he could animate the various fingers (Node 15). In response to Ross's request for assistance, Ted coached him through the process, occasionally using Ross's mouse to demonstrate his points (Node 16). Later that same day, Sam, who had been eavesdropping on Ross and Ted (Node 17), began to animate a door he had been working on (Node 18). Sam was having difficulty and asked the technology teacher for assistance (Node 20). The technology teacher had been watching and learning as Ted used the wire-frame mode (Node 19), and he shared his understanding of this practice with Sam, occasionally asking Ted for clarification (Node 21). Although Ross and Sam had begun to incorporate the practice into their models, only Ted was able to make his object move across the stage so that it appeared that the children were still grouped with the parent (Node 22). The education teacher then called all students together and asked Ted to share his understanding of parent–child relationships (Node 23). Ted explained how it relates to making objects animate, clarifying what he was saying by demonstrating it on the computer (Node 24).

Some students seemed to grasp how the concept could be employed to successfully create an animation, illustrated when Sam said to the education teacher (Node 25), "Oh, so this (pointing to the person) is the parent and the arm is a child." However, others appeared confused and, in one case, extremely frustrated. This frustration manifested itself on Day 4 (Node 26) when Jim, who was being helped by Ross, became extremely frustrated and yelled out "This doesn't work, I don't get what I am supposed to do." Zak then went over and explained parent–child relationships and its relevance to animation to both Jim and Ross (Node 27). This explanation involved pointing to the screen and alluding to the particular task at hand: "You see this finger is the child and the hand is the parent." Jim did not understand the relationships and stopped listening to Zak, but he continued trying to animate his object (Node 28). Ross, however, did understand the concept and the practice and returned to his computer where he made his character open a door (Node 29).

Later, when Jim's animated character, Mr. White, walked across the screen with his feet remaining planted at the original location, his frustration again elevated (Node 30). The education teacher then pointed to the child and parent buttons and said, "Use these after highlighting the objects" (Node 31). Jim, growing more frustrated, commented (Node 32), "I don't know what parent and child mean." Ted then came over and asked Jim to show him what he was doing. When Jim neglected to group the children, Ted pointed to the screen and said (Node 33), "That is what you did wrong. You didn't group those objects with the parent." Jim then watched Ted work back on Ted's machine, as Ted modeled the practice (Node 34). Afterward, Jim returned to his own computer and worked at ungrouping and grouping objects so that he could move the character correctly (Node 35). He finally got it to work and then described parent–child relationships to the education mentor in terms of how it helped in programming:

> It allows me to group a whole object but makes one of the pieces a child [Jim points to the knee] and I can move it and group them back so I can make the object look like [it is] moving. By grouping some and not others, I don't have to animate each object but just parts, and the rest stays together.

His explanation captured the relationships of his conceptual understanding (parent–child relationships) and his particular practices.

Examination of the dialogue within particular nodes showed how the practice of animation transformed over time (i.e., their contextual influence). Initially, students were more concerned with aesthetic appeal and realism (Nodes 5–35); for example, by using each other as models to determine how to make a character's walking animation look realistic. However, by the end of Days 4 and 5, realism was secondary to the need for completion (Nodes 35–53, not shown in Figure 7). Time efficiency eventually became the more salient constraint on defining the practice, with one student stating, "Why don't we simply have Mr. White slide across the stage . . . . At this point I'm less concerned with how it looks. I just want to get him from one side of the stage to the other." Furthermore, learner specialization for a particular type of animation began to emerge. By Day 5, the group had made one learner responsible for all walking, whereas another dealt with head turns, and still another focused on arm movement and animating the fingers of the monkey's paw. One student stated, "Okay, Ted will do all the walking stuff and Sam will do body movement."

Cross-Case Comparison

Learning by design. Students in both groups engaged in a design process similar to experienced designers as they shifted between learning software tools, constructing their models, and visualizing their models, as their skill in using the software and their understanding of the problem at hand evolved. Furthermore, through this design process, conversations evolved surrounding the constraints (timelines and resources) and affordances (available tools and expertise) as they related to completing the task. For example, one of the strengths of emerging three-dimensional technologies is that they allow for the placing of viewpoints. This functionality opens up many learning opportunities not normally available to beginning astronomy students. For example, a student wishing to view the Earth from the moon would traditionally be relegated to viewing static pictures that show the Earth from the moon. By using viewpoints, however, a student can design a model that has a viewpoint on the moon and observe the Earth, determine whether the Earth has phases, as well as visualize other astronomical concepts that can be understood by gaining a different perspective.

One exciting feature of learning astronomy in this context was how the building of their models created an authentic reason for applying mathematics. Applying mathematics was central to dispelling misconceptions about astronomy (e.g., issues of scale). Through building their models, students engaged numbers and equations through the direct manipulation of their virtual objects, supporting them in building an understanding of quantitative relations of astronomical phenomena without defining these through their formalisms. It was significant to hear one student say, “Wow, finally a use for math!” Consistent with how students came to understand other conceptual tools, mathematics was not introduced as a set of rules to be memorized but as a collection of useful tools to support students in building their three-dimensional worlds.

Despite the success that the solar group had in designing a model solar system, constraining issues did emerge. For example, the teacher at times steered the students toward constructing a model based on her vision of what she expected the students to learn. As a result, the design task (construct a solar system) shifted from an open-ended, student-driven task to a narrower goal of constructing a model that imitated the instructor’s image of a satisfactory representation of the solar system.[6] The addition of this design constraint changed the nature of the design process from an iterative model-building process that generates questions to spur scientific

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[6] Although at a general level the task was reproduction, at the level of local activity the students engaged in much appreciation and decision making (e.g., making decisions regarding level of detail and deciding whether to develop scientifically accurate models vs. models that were more useful in supporting the user in using the model to develop astronomical insights, or even deciding which moons and what information would be included and excluded from the model).

inquiry to one more heavily focused on imitation. This robbed the students of the need to develop those design skills.

In contrast, the theater group was immersed in a design process similar to that described by Schön (1987), in which the students developed meaning through creating designs to solve a problem rather than having meaning imposed by the problem or some other external agent. In other words, the students could impose their own meanings and define their goals before and during the design process while overcoming various constraints to complete their design. For example, at one point, the students realized that a deadline (constraint) was approaching, and to have their play ready, certain sacrifices would need to be made in animating their characters. In addition, the theater group had the opportunity to view their play from multiple perspectives. For instance, each student was simultaneously the director, producer, set designer, and sound designer for their entire virtual three-dimensional production.

Differences in emergent tasks and constraints. The solar group developed a model of the solar system and, in the process, group members became increasingly knowledgeably skillful with three-dimensional modeling and astronomy. The solar group activity, especially when considered in contrast to the theater group, was oriented toward reproduction rather than original creation. The solar group focused on modeling the solar system as it is defined by scientists and made public through available resources, especially textbooks, the Web, and their teachers. The solar system teachers had a clear idea of what they expected students to produce, and deviations from the scientifically accepted solar system were considered wrong. This predefined endpoint potentially resulted in different sorts of activities than those engaged in by the theater group, with replication and fact enactment being valued more heavily than learner creativity. Had the solar group conceptualized their activity as one of model building in which the challenge lies in constructing models that answer scientific questions (vs. one of reproduction), more creativity might have been engaged. In contrast, the theater group decided early on to take liberties in adapting the play, and the teachers were comparatively more open to having students define the parameters of the project. Therefore, the project constraints that emerged for the theater group were much more open-ended and student directed than for the solar group.

Furthermore, the theater group members were cognizant of the audience for their project, often (48 out of the 242 recorded nodes) referring in their discussions to the friends, family members, middle school students, and Internet viewing audience who would use their project. In contrast, the solar group seldom discussed audience constraints, discussing audience or constraints of the Web-based delivery environment in only three recorded nodes. This difference suggests that a more socially authentic context emerged for the theater activity than the solar system activity. In sum, whereas the theater group could best be described as a context of collaboratively emergent public constraints, the solar group could be better characterized as a context of teacher-defined, factual reproduction constraints.

Group dynamics and evolution. Divisions of labor and the role the teacher played impacted the way both the solar group and the theater group unfolded. In the theater group, over 90% of the nodes (216 out of 242) involved a student, sometimes with a teacher, as an initiator. (Using the CN-ARE approach, it is possible for both a student and a teacher to dually initiate a node.) Initially, the teachers directed the trajectory of experience by remaining the focal point for conversations, taking notes, and initiating group discussions. However, on Day 2 there was a switch in teacher-only initiation when one teacher was distracted in conversation. The students, growing impatient, seized the moment and actually walked over and removed the easel from his hands. From that point forward, the learners took responsibility for the project's completion, with the teachers stepping in only when the learners were getting sidetracked or to address a technology-based impasse. At these times, the teachers would rarely tell students what to do. Instead, they used questioning techniques to help students maintain or reinitialize the goal. Their approach was consistent with that of Collins, Brown, and Newman (1989) in which the teacher models, then coaches and provides scaffolding, with the goal being to gradually fade to the background, applying supports only when necessary. On the first day, the teacher often led discussion and modeled the use of CosmoWorlds, whereas on Days 3 through 4, the teacher coached students while they worked on their projects; and by Day 5, the teacher faded into the background, encouraging the learners to assume responsibility for the completion of their project.

In the solar group, only 59% of the nodes (140 out of 238) involved a student as an initiator. More striking, one of the teachers was involved in initiating 60% of all coded nodes and in all but 3 of the 22 planning nodes. In contrast to the theater group, the solar group teachers had a difficult time stepping back, promoting collaboration, and allowing the students to develop ownership and responsibility for their projects. The switch from teacher initiation to student initiation never took place in the solar group. There was little collaboration among the students unless explicitly requested by the teachers. Furthermore, the teachers continually competed with the computers for the attention of the students. This led to different group dynamics for the two groups.

We developed a qualitative visual representation of the interaction among students and teachers for the theater group and solar group across time (see Figure 8). This depiction represents an encoding of the observations initially taken from field notes, which was then followed up with feedback from the directors and through further analysis of the videotapes by the research team to increase representational accuracy. Therefore, although the diagram is a qualitative representation, we have used multiple sources of data to triangulate this interpretation. The specific distances are not based on a quantitative scale; rather, they are intended to qualitatively represent the relations we observed. This depiction shows that early in both projects the facilitators, represented by black circles, were the center of activity and interaction, with all discussion flowing through them. In the theater group,

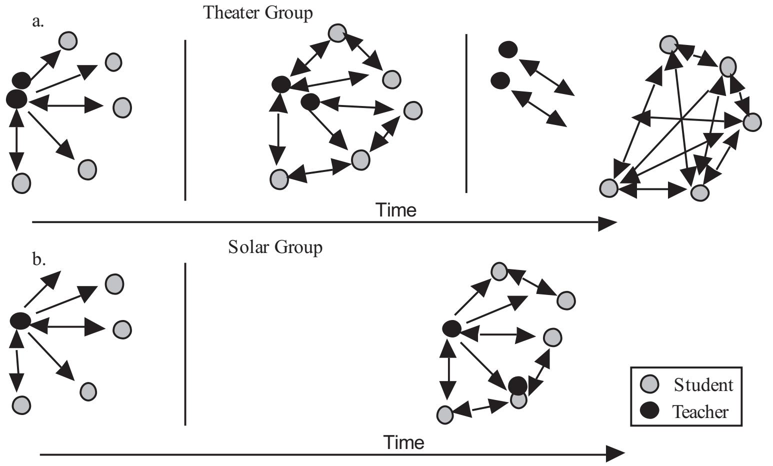

FIGURE 8 Pictorial representation of the interaction among students and teachers across time. This depiction represents an encoding of the observations initially taken from field nodes, which were then followed up with feedback from directors and further analysis of the videotapes by the research team to increase representational accuracy. Gray dots represent students and black dots represent teachers, with placement of dots roughly signifying distance between individuals. Solid lines suggest movement and dialogue.

group members quickly began sharing information on CosmoWorlds. In the solar group, this pattern of interaction did not emerge until much later in the week. The theater group evolved even further by the end of the week, with the group members working almost entirely independently, interacting together in both small and large groups without their teachers. The teachers were facilitators in these latter stages, entering the discussion to provide just-in-time instruction, Socratic questioning, or to help the group monitor its progress.

CONCLUSIONS

In this research, we followed the trajectory of two practices to document empirically how practices (e.g., geometric transformation) and conceptual understanding mutually coevolve, and we suggest that both terms can be subsumed under the term knowledgeably skillful. Even when concepts were discussed as issues at hand (vs. being treated as part of practices), their realization reciprocally emerged within the context of their actualization as a practice. Such a pedagogical approach directly speaks to Sfard's (1998) distinction between acquisition and participatory metaphors of learning, or Lave's (1997) distinction between a "culture of acquisition" versus “understanding in practice,” by suggesting that the goal of instruction is to facilitate participation in practices that involve conceptually rich understanding and to situate conceptual discussions as part of student tasks and practices. We have attempted to document how conceptual understanding did not evolve as some reification of practice or as an abstract entity, but was distributed across students’ trajectory of experiences with teachers, each other, technology, and the task at hand. It is our contention that adopting the participation metaphor contextualizes knowing as a relational process and not only more usefully captures the world as it is, but also dramatically augments and shapes the practice of designing environments to support learners in becoming knowledgeably skillful.

Rooted in Cartesian dualisms, separating knowing and doing is long and distinguished in the history of cognitive science, education, and Western thought in general (Barab et al., 1999; Bredo, 1994; Cunningham, 1992; Swenson, 1997). This is apparent in the separation of conceptual and procedural knowledge (Alexander, 1996; Greeno, 1978), and this dualism has been reified throughout traditional American schooling (Lave & Wenger, 1991; Resnick, 1987). As Cunningham (1992) wrote, “The majority of the pedagogical practices employed in our culture (e.g., lectures, large classes where listening predominates, objective tests with ‘true’ or ‘best’ answers) are ideally suited to supporting a dualist perspective” (p. 179). Specifically, these practices have involved teachers lecturing on prepackaged concepts with the expectation that learners will later match up the concepts with their functions (J. S. Brown et al., 1989). In contrast, we and others have argued for the inextricable relations of knowing and doing, and we find ourselves resonating with notions such as knowledgeably skillful (Lave & Wenger, 1991), intelligent action (Ryle, 1949), mind as action (Wertsch, 1998), and the process of semiosis (Cunningham, 1992).

We, as designers, attempted to avoid these dualisms by immersing camp participants in rich contexts that demand thoughtful action. While working in these contexts, participants manipulated and examined dynamic artifacts they developed with three-dimensional modeling tools. At one level, theorizing knowing and doing as inseparable is simply a theoretical commitment that we have chosen, and their interrelations are present because we have chosen to situate them in this manner. However, at another level, we believe that situating our camp design and our interpretations in terms of this commitment allows us to develop more useful learning environments and interpretations of the student experience in these environments than if we maintained the dualistic tradition. With respect to design issues, this commitment led to the creation of a project-based learning environment, which is one type of PLE in which completing a project provides a motivation and justification for students’ evolving practices—practices that require rich conceptual understanding. For example, the concept of relative size was not a separate activity that students designing a model of a solar system were expected to study; rather, it was a way of defining the constraints of their virtual worlds, with learners actualizing and evolving their understanding as part of the model-building process. Similarly, students in the theater group did not learn parent–child relationships as an abstract concept but, instead, came to appreciate its application in terms of the complex practice of animation.

One could view both of these instances as learning a concept and then applying it or even looking at learner activity as simply mechanistic behaviors after which learners developed conceptual understanding. However, we believe that it is more parsimonious and functional to discuss these instances as learners becoming knowledgeably skillful without trying to separate out what was knowing and what was doing. Cleaving learner activity along dualistic (mind vs. body or mind vs. environment) or even researcher-imposed lines serves to carve up experience in ways that were inconsistent with our observations. We observed that learning involved a trajectory extending across multiple time scales, resources, individuals, and activities. Relegating experience to conceptual understanding occurring in the confines of the mind creates an unnecessary divide between individual and environment (Gibson, 1979). This separation further justifies the validity of posttest analysis and allows researchers to overlook the complex and dynamic interactions that characterize learning in PLEs (Barab & Kirshner, in press).

It would also be naive to refer to either of the practices discussed, or any other practices, as simply mechanistic behaviors. The theater group never explicitly used theater formalisms of blocking, perspective, aesthetics, and so forth. Their model-building practices, however, clearly evidenced an appreciation for audience and made good use of blocking, perspective, and aesthetics. We would have a difficult time referring to their practices as behavioral but not knowledgeable. In other words, these practices relied on conceptual understanding even though no one used the particular formalisms taught in theater or mathematics classes. It is for this reason that we use the phrase knowledgeably skillful when characterizing learner practices. Similarly, the practice of geometric transformation was informed by tools, resources, and other experiences, with learner understanding and practices being situated in and part of these contexts. Students in the solar group did not come to appreciate the magnitude of the differences of scale, presumably a conceptual understanding, until they enacted these differences in the context of building their models. Students in the theater group came to understand parent–child relationships within and through their local activities. Restated, knowing and doing are so interlinked that it would be counterproductive to build accounts of cognition or to create learning environments that treat them as separate.

The inextricable relations of knowing and doing were also contextually influenced, being defined in part by teacher-defined prescriptions but primarily through the constraints of student-defined goals and expectations with respect to their projects. For example, despite the education teachers' explicit lecturing on parent–child relationships, students' understanding was a part of and evolved through the practices and tasks they were carrying out. The contextual influence on practice was evident in the evolution of animation, which began with the goal of producing real-looking movement and became relegated to the goal of efficiency. Although both goals require animating objects, the process and task of animation are different in that one emphasizes texturing objects in fine detail and creating multiple children that can be animated separately, whereas the other requires making more time-efficient choices. The ability of students to alter practices in relation to contextual particulars is a necessary understanding of practices if they are to have real-world application. All too often, however, in schools we provide students with a definition of practice or provide them with the opportunity to apply the practice within the constraints of one close-ended assignment that requires little or no adaptation of what is being learned.

In addition to the influence of context on practices were the effects of resources on practices and, ultimately, the greater context. These effects on a group or community dynamic can be remarkable, relegating practices passed on from generation to generation and hours of work to meaningless relics of the past. Roth (1996) discussed how a glue gun tool undermined much of the teacher-adopted curricular goals because, with the glue guns, students no longer needed to understand many of the important concepts the lesson was designed to illuminate (e.g., triangulation). Similarly, we were able to document how the introduction of a predeveloped artifact (the door for the theater group) affected the individual, the group, and the relationships among both. These artifacts have the potential of undermining individuals (whose personal identity is devalued) as well as entire communities (e.g., dairy farmers) whose practices (those milking with their hands) are not as efficient and profitable as those accomplished using technological artifacts (e.g., the farmer who purchases an electronic milker). In this project, the CD-ROM of images seemed like an innocuous introduction, but it quickly redefined the community. This case shows how technological innovations can have a profound impact on the learning practices and classroom culture, and designers of PLEs should be aware of their potential impact on a community.

Last, the virtual instantiation of students' understanding afforded by three-dimensional models facilitated the development of grounded understanding of astronomical phenomena not as isolated concepts, but as distributed descriptions that are situated across their experiences (Barab et al., 1998; Pea, 1993). For example, students in the solar group were able to create artifacts and enter various coordinates, sizes, rotations, and tilts to explore (and challenge) their current conceptions of the solar system. This is important because astronomy is a domain that traditionally does not allow learners to experience planetary and stellar dynamics; instead, learners typically read about them in a textbook. Clearly, students cannot travel to the heavens, but three-dimensional modeling tools allow students to have local experience through which their astronomical understanding can evolve. With respect to the theater group, learners were able to set up scenes and then immediately observe the effects of design decisions related to theatrical formalisms, such as blocking, lighting, and casting. In addition, each student was able to play the director, producer, set designer, and even actor for their three-dimensional production.

IMPLICATIONS

It is important to reclarify our claim that conceptual understanding and contextualized activity are fundamentally interrelated and mutually constitutive. We provide support for our conviction that conceptual understanding coevolved through learner practices, leading to what Lave and Wenger (1991) referred to as becoming knowledgeably skillful. We are not implying that these understandings are a result of virtual artifacts serving as a source of perturbation for learner cognitive structures or that what is being constructed is some sort of reified mental structure. Rather, while working with three-dimensional modeling tools in our PLEs, students can participate in a trajectory of experiences that supports their becoming knowledgeably skillful—a learning process that involves participation and not accommodation or acquisition (Barab & Duffy, 2000; Kirshner & Whitson, 1997, 1998).

A challenge in our design experiments is to develop innovative introductory astronomy courses that embed the factual constraints within a context of emergent task constraints (Barab, Hay, Barnett, & Keating, 2000). This effort involves supporting students as they use three-dimensional modeling tools to collaboratively define meaningful questions and construct VR models that they and future users can use to answer these student-generated questions and to better understand astronomy. Although factual constraints still hold, they are introduced by students in relation to constructing their models as opposed to being didactically imposed by the teacher (Barab, Barnett, et al., in press). In addition, technological advances since this summer camp have made it possible to implement these types of three-dimensional modeling projects with fifth graders on standard laptop computers using free software.

An important implication of this research stems from the acknowledgment that PLEs are continually evolving systems that support learners at multiple points along their trajectory of being and becoming knowledgeably skillful. The emergent and dynamic nature of PLEs has important implications for the nature of instructional design. Rather than traditional paradigms aimed toward specifying fixed goals and objectives using predetermined lessons directed toward students' acquisition of facts (see Reigeluth, 1983), the emergent practices defining these types of environments push toward a new educational paradigm (Barab et al., 1999; Bednar et al., 1992; Gagne, Briggs, & Wager, 1993; Reigeluth, 1999; Roth, 1996):

> This new paradigm has to recognize that the needs of practice relative to changing systems of a community's activities are more apt regulators of learning than are the community's (including teachers') beliefs about the importance, significance, and value of isolated pieces of concept-related resources and practices. In many respects,

> this knowledge-building community had properties similar to other self-organizing and emergent phenomena; the evolving resources and practices provided not only a base for future events but also new possibilities and constraints for still other events. (Roth, 1996, p. 217)

If the practices that students learn change with respect to contextual demands, then it is essential that educators do more than simply tell or show students how to carry out a particular practice; rather, they need to establish learning contexts that encourage students to engage in and, possibly more important, to modify practices in response to various contextual demands. It is the responsibility of the teacher to support the emergence of learning environments that both (a) validate the importance of to-be-learned, conceptually rich practices, and (b) require learners to continually evolve their competence in response to changing contextual demands.

We have also found that it is important that the teacher has "buy-in" into the pedagogical practices that supply the foundation of PLEs; that is, allowing the opportunity for the emergence of student-driven practices, goals, and expectations rather than redefining the goals to meet certain curricular objectives. Stated more broadly, teachers must buy into the participation and not simply the acquisition models for learning (Sfard, 1998). From a design perspective, one of the greatest challenges facing instructional designers is not how to design innovative curricular packages, but, rather, how to support teachers in using them in a manner that is consistent with designers' intentions. For example, when the CTGV (1990, 1993) published the Jasper Series, they found that many teachers tended to integrate the series into traditional pedagogical practices, many of which were inconsistent with the participatory contexts that the series was designed to promote.

The emergent nature of these environments and of the process of learning also has implications for research. Central to our research is a participatory unit of analysis, defined as the intersection of individual, context, and activity as they unfold in situ. Limitations to the more common unit of analysis that focuses on the thinking of individual learners is evident in Greeno's (1998) statement:

> Cognitive science analyzes structures of the informational contents of activity, but has little to say about the mutual interactions that people have with each other and with the material and technological resources of their environments. (p. 6)

The difficulty in finding methods for capturing the more dynamic unit of analysis discussed in this study lies in the fact that this unit is distributed spatially and temporally across multiple individual, social, and material components (Barab & Kirshner, in press). Despite the challenges in capturing such a dynamic and distributed unit of analysis, it is imperative that educators continue to explore innovative methodological approaches that capture learning as it emerges within rich environments so as to inform instructional practice and design. We have found the

CN-ARE methodology, introduced by Barab, Hay, and Yamagata-Lynch (in press), to provide a useful strategy for tracing the evolution of resources and practices within a PLE. These findings can provide educators with an understanding of the types of interactions PLEs afford, potentially serving as guideposts for designers and teachers. The CN-ARE approach allowed us to capture and develop networks that can represent the interaction among the task, the individual, the teachers, the technology, and the physical–social setting.

We believe that three-dimensional technologies create exciting opportunities for students to create, manipulate, and interact with their own virtual products, developing understandings through their first-hand experience—especially with respect to astronomy learning. When students learn concepts that are introduced as somehow disembodied and abstract, they must suspend reality and conceptualize signs (e.g., mathematical symbols and line of nodes) void of any concrete attachment to direct experience (Walkerdine, 1997). As such, students must construct their own signs, some of which correspond with socially negotiated meanings established by authentic communities of practice and others that do not. With respect to astronomy, this has resulted in widespread alternative conceptions about the scale of the solar system and other important astronomy concepts (Pfundt & Duit, 1998; Pyramid Film & Video, 1988; Wandersee et al., 1994). We have argued that for students participating in this summer camp, conceptual understanding was inextricably linked as part of practice and stood in sharp contrast to their more common treatment in schools in which abstract facts are introduced through didactic lectures or textbooks (Bransford, Franks, Vye, & Sherwood, 1979; Ruopp, Gal, Drayton, & Pfister, 1993). The constructionist nature of the course and the innovative technology also proved engaging for students who chose to participate and do what could be characterized as curricular work voluntarily, when school was out—these technologies can stimulate student interest in educational activities during their free time.

Learning through design can also support additional opportunities in which students can develop a sense of authorship over their work (Holbrook & Kolodner, 2000; Lehrer, 1993). This feeling of authorship can lead to increased intrinsic motivation and perhaps a stronger interest in the subject matter under study (Lepper, 1988). Furthermore, learning by designing models can increase student motivation by allowing the freedom to control and determine the course of their activities (Lepper & Malone, 1987). When students learn collaborative design skills, they are developing habits and practices that are valuable for their future endeavors (e.g., learning how to plan, recognizing when a course of action is not working, becoming comfortable with learning how to use new tools, and learning how to negotiate and arrive at a shared understanding of how to solve complex problems; Ehrmann & Balestri, 1992).

In closing, we believe it is important to note that our understanding of the emergent nature of PLEs and the interrelations of knowing and doing is not based on some theoretical conjecture, but rather arises out of our experience with facilitating and analyzing the development of PLEs. Because of the grounded nature of this research (both its direct tie to actual data and the fact that the data are derived within an authentic, naturalistic setting), it can inform practice and practitioners in meaningful ways. This type of empirical research is needed to advance our understanding of PLEs. We hope that educators will continue to explore innovative techniques for capturing the unfolding of learning and group dynamics in situ so that we can build a grounded understanding of what is occurring and the types of interventions and design principles that need to be considered while developing PLEs. Our interpretations of the data suggest uniting the traditionally distinct notions of knowing and doing, reconceptualizing both as a process of becoming knowledgeably skillful. These results also indicate the potential of PLEs for supporting this process.

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