Classroom Space, Classroom Time, and the Representation of Dynamic Phenomena

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Introduction

In 1973, Austrian ethologist Karl von Frisch was awarded the Nobel Prize in Physiology for his pioneering work on communication among insects, in particular his discovery of the "waggle dance" that honey bees use to communicate the direction and distance of food sources to hive mates (von Frisch, 1923, 1946, 1967). The prize was a long time in coming. Von Frisch began his study of bees in the early 1920s. Controversy over his theory persisted until 2006, when British scientists successfully used harmonic radar techniques to track the flight of bees and confirm von Frisch's theory (Riley, *et al.*, 2005). The work, consuming long stretches of von Frisch's career, involved careful experiments separated by long periods of detailed observation and the identification of patterns of movement of bees within specially designed hives with glass walls.

Von Frisch's experience was far from unique. In disparate scientific fields such as astronomy, earth science, biology, and even particle physics, much of the day-to-day work is very much a waiting game, requiring the accumulation of evidence based on the observation of infrequent, asynchronous events occurring over time courses measured by the calendar rather than the clock. This kind of research places a premium on persistent access to the dynamic phenomena under study, adequate preparation for the capture of events, the careful recording of observations, and the systematic hunt for patterns found within data. In short, it demands patience.

Providing opportunities for learners to engage in this kind of "patient science" in elementary schools poses a significant challenge. Curricular demands make it difficult to devote significant class time to the study of a single phenomenon. Partitioning the school day into disciplinary periods makes it hard to respond to asynchronous events. While the class of affordances that Perkins (1991) labels *phenomenaria* are not uncommon in classrooms, it is difficult to sustain long-term phenomena that require classroom space and maintenance (feeding mice, maintaining power to the aquarium, etc.), and that are limited in content domain to phenomena that physically "fit" within the physical classroom.

Given the difficulty of managing long-term investigations, it is not surprising that elementary teachers are not employing them as a significant component of their science instructional repertoire. An NSF-sponsored survey of the nation's elementary school teachers (Fulp, 2002) found that less than 10% engaged in extended projects or investigations on a regular basis. Computer simulation can provide classroom access to a broader range of phenomena, and also has the advantage of offering practitioner control over the pace and representation of those unfolding phenomena. But relatively few teachers consider themselves well prepared to use computers for collecting or analyzing data (32%), demonstrating scientific principles (20%), or conducting laboratory demonstrations (13%). And so they don't. Only 6% of elementary students use a computer once a week as a tool in science class, 2% use computer simulations, and 1% collect data using sensor or probes (Fulp, 2002).

Over the past three years, we have defined and begun to explore the affordances of a design framework that we call *Embedded Phenomena*, intended to support such “patient,” extended classroom investigations (Moher, 2006). The design space of the embedded phenomena framework is characterized by four common elements:

- Simulated dynamic scientific phenomena are “mapped onto,” and asserted to occur within, the physical space of the classroom.

- The phenomena are represented through distributed media (conventional classroom computers) located around the classroom representing “portals” into that phenomenon, depicting local state information and control affordances corresponding to the mapping between the room and the phenomenon. (Embedded phenomena are “delivered” using our “Phenomenon Server,” a web portal that supports configuration and scheduling of the simulation for delivery to any Internet-connected computer running a conventional web browser with a Flash plug-in.)

- The simulations are persistent, running and being presented continuously over extended time periods, concurrently but asynchronously with respect to the regular instructional flow.

- As individuals, in small groups, and as whole classes, students monitor and manipulate the state of the simulation through those media, gathering evidence to solve a problem or answer a question.

The framework “embeds” learning in both space and time. Learners are *spatially embedded* by situating their activity (and their representations of accumulating evidence) physically within the phenomenon under investigation. Learners are *temporally embedded* within the time course determined by the simulation of the phenomenon itself, rather than the time course of classroom instruction. This “here and now” approach embodied by the embedded phenomena framework stands in contrast to the “there and then” nature of much of traditional science instruction. The central conjecture underlying this work is that this dual embedding, within the context of appropriate instructional designs, can have beneficial impacts on cognitive and affective learner outcomes.

We have designed and implemented three illustrative systems and deployed them in over a dozen elementary school classrooms within the context of instructional units on seismology, insect ecology, and astronomy. In a series of empirical studies, we have presented preliminary support for the conjecture that the embedded phenomena framework can positively impact individual learner outcomes in the development of skill in science practice, conceptual learning, and the development of stances as legitimized investigators (Moher *et al.*, 2004, 2005, 2006; Barron *et al.*, 2006; Thompson & Moher, 2006; Moher, 2006). In the discussion that follows, we will briefly describe the outcomes of those studies. But the primary goal of this paper is to introduce the concept of embedded phenomena to the AERA community and to make the case for the embedded phenomena framework as a paradigm worthy of further exploration.

Related technologies

Simulations have long been used in support of science inquiry learning, using a variety of media including desktop-based microworlds (e.g., DiSessa, 1997, Papert, 1980), first-person virtual environments (e.g., Barab *et al.*, 2000, Dede *et al.*, 1997, Moher *et al.*, 2000), and distributed handheld devices (e.g., Danesh *et al.*, 2002, Vath *et al.*, 2005; Vahey, *et al.*, 2004; Roschelle & Pea, 2002). Simulations broaden the space of accessible phenomena and afford the introduction of simplifying abstractions that scaffold learning. Embedded phenomena draw particular inspiration from simulation systems that enable students to serve as embodied participants (Dourish, 2001; Resnick & Wilensky, 1997) engaged in the enterprise of authentic scientific investigation, and from the inspiring concept of participatory simulation (Colella, 2000, Wilensky & Stroup, 1999).

Several recent projects have begun to employ embedded ubiquitous computing media to support science learning (Price & Rogers, 2003; Rogers & Price, 2004). In the Hunting of the Snark (Price *et al.*, 2003), young children seek to discover the characteristics of the mythical Snark by interacting with a variety of ambient media situated within a classroom. A range of technologies, including RFID tags, accelerometers, pressure pads, and location tracking devices allow children to explore Snark characteristics in multiple modes of activity. In the Ambient Wood projects (Randell *et al.*, 2003), probes are used in conjunction with fixed-location "kiosks" that serve as complementary data sources. In Environmental Detectives (Klopfer *et al.*, 2002), activities situated in outdoor spaces are augmented with PDAs that provide simulated data on environmental parameters. In Savannah (Benford, *et al.*, 2004; Facer, *et al.*, 2004) In Savannah, a group of students assumes the role of a pride of African lions intent on survival. In an outdoor setting, equipped with GPS-augmented wireless-networked PDAs, they roam the environment looking for food and water sources, safe resting places, and predators that threaten their existence. Like embedded phenomena, these innovative projects employ embedded displays to represent the state of dynamic (simulated) phenomena. They differ from the embedded phenomena framework, however, in that the representation of phenomena is not persistent; the use of these systems is synchronized within the regular flow of instruction.

From an interaction perspective, embedded phenomena represent an exploration of the “other side” of the ubiquitous computing paradigm: instead of mobile media, here the focus is on the affordances of ambient media. Embedded phenomena support the collaborative activity of workgroups through the use of multiple media devices distributed within a single physical space, a popular deployment framework in CSCL and CSCW (e.g., Abowd, 1999; Wilensky & Stroup, 2000; Greenberg & Rounding, 2001; Huang & Mynatt, 2003). In such systems, public affordances provide focal points for informal discourse and activity that complement individual work undertaken in private. Embedded phenomena are distinguished from these systems by their complete absence of private affordances; in this way, they more closely resemble a multi-display variant of single-display groupware (Stewart *et al.*, 1999) in which all interaction is undertaken publicly on shared devices. And while they share with ‘roomware’ projects such as iRoom (Johanson *et al.*, 2002) and i-LAND (Streitz *et al.*, 1987) the notion of the designed physical space as the interface to the computational system, in embedded phenomena multiple devices are used not to partition information by functionality (Grudin, 2001), but rather as a means of distributing the representation of state over physical space, requiring users to attend to multiple affordances in order to understand and/or control the state of the ongoing simulation. Like ambient displays (Wisneski *et al.*, 1998), embedded phenomena are designed to provide representations of persistent, dynamic phenomena. Although ambient media are often associated with non-display-based *fixtures*, and represent real, rather than simulated phenomena, a more important distinction concerns the peripherality of ambient media, in the sense that they provide access to "non-critical" (Mankoff *et al.*, 2003) information that is not necessarily of ongoing or central concern to their users. Embedded phenomena fall somewhere between the “take it or leave it” nature of ambient displays and the exigency of data in traditional CSCW and CSCL applications.

Embedded phenomena share with virtual, mixed, and augmented reality systems the goal of inducing among users senses of immersion (fidelity) and presence (“being there”) (Slater & Wilbur, 1997). While embedded phenomena are manifested as sparse, low-fidelity “portals” into simulated phenomena, we seek to enhance the salience of the activity by maximizing the size of the imagined phenomena and placing the user within its physical midst, participating in authentic scientific practices. Embedded phenomena differ in that they introduce a new "flavor" of artificial reality, one characterized not by an attempt to substitute one reality for another, or to bridge the natural and artificial worlds, but instead allow distinct natural and artificial worlds co-exist in time and space.

Embedded Phenomena applications

RoomQuake. *RoomQuake* is an earthquake simulation application. Students collectively adopt the pretense that their classroom is an active seismic field, and that a series of earthquakes is expected over the course of several weeks within that field. The challenge posed to the students is to determine the location of a “fault line” running through the classroom, and to see if they can detect any patterns in the magnitude and timing of seismic events. Classroom computers serve as simulated seismographs that depict continuous strip-chart recordings of local vibration (seismograms), where locality is conditioned upon their specific placement in the classroom. Most of the time, the seismograms reflect a low level of background vibration. At (apparently) unpredictable times, a crescendoing rumble from a subwoofer situated in the corner of the classroom signals the occurrence of an earthquake. Upon this signal (or as soon thereafter as classroom instruction permits), students move to the seismographic stations to read the waveforms.

Reading the seismogram waveform recorded at a single location provides two critical pieces of information: the magnitude of the event, and the distance (but not direction) of the event from the recording station. Determining the epicenter of an earthquake requires readings from multiple sites, which may be combined together through the process of *trilateration* to obtain a solution. In RoomQuake, we use calibrated dry-lines anchored at the seismographs to sweep out arcs of potential epicenter loci; the solution is obtained when the students at the end of those lines converge at a common point. Once the location and magnitude have been determined, the teacher hangs a color-coded (representing magnitude) Styrofoam ball from the ceiling at the epicenter point, providing a salient historical record of the event series, and students update poster-based representations of the temporal and intensity distributions of the events. After experiencing a series of 15-25 earthquakes spread over six weeks, students engage in discussions about their data to determine fault lines and reflect on patterns of earthquake activity and the possibility of plate movements as a possible cause. Figure 1 illustrates the complete process.

RoomQuake has been used in a half-dozen classrooms ranging from grades 5-7, including two trials instrumented to assess learner outcomes. Performance on skill acquisition tasks showed a high level of competence during both trials; 70-90% of students were able to demonstrate mastery on articulated component skills associated with interpreting seismograms, including arrival latency of ground waves[1], determination of graph maxima, use of a nomogram[2] to calculate magnitude, and identification of epicenter loci. While students were able to physically demonstrate the process of trilateration, translating that skill to a paper-and-pencil explanation was less successful, with only about 40-60% capable of constructing (trial 1) or selecting (trial 2) an appropriate rationale. Student understanding of event parameter distributions proved strong, with 80-90% of students predicting linear or curvilinear spatial distributions and an inverse relationship between event magnitude and frequency. A pre-post comparison with a non-treatment group in trial 2 confirmed a significant learning effect relative to pre-unit conceptions, as well as significant increase in preference for learner's personally developed evidence over appeals to textbook and teacher authority[3].

RoomBugs. RoomBugs simulates the migration of bugs in a small farming community. Horizontally oriented tablet computers are used to suggest "sandboxes" traversed by insects. As the bugs cross the sandbox, they leave characteristic tracks that vary depending on species (Figure 2). By consulting an accompanying "field guide," learners distinguish one kind of track from another and identify the species of the bugs that crossed the sandbox. Four control affordances are provided: (a) the ability to "smooth out the sand" to create a clean palate for observing tracks, (b) the ability to introduce one of three types of pesticide in an attempt to reduce the infestation of undesirable bugs, (c) the ability to control the amount of moisture in the local area of the sandbox, and (d) the ability to leave marks in the sand using a stylus as a simulated "stick." This final capability was provided to support learners in the task of counting tracks, ensuring a comprehensive and non-redundant survey.

RoomBugs has been used in one fifth grade and two sixth-grade classrooms. In an instrumented three-week unit on animal ecologies, we deployed four networked "sandboxes" in different locations within a sixth-grade classroom. A simulation engine was used to dynamically generate the bug tracks based on initial population distributions and local environmental conditions (moisture, pesticide presence). Conservation of bug populations was maintained; when local conditions drove them out of the area of one sandbox, rather than dying off they migrated to other sandboxes (or interstitial regions between traps). The field guide gave clues regarding which bugs fell into each category, and was reinforced with the printing and classroom distribution of a semi-weekly "local newspaper" that reported local farmers' observations of bugs in the various "parts of town" represented by the sandboxes, and their impact on crop yield.

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[1] Event distance is proportional to the difference between the arrival times of two types of ground waves with readily identifiable waveform signatures.

[2] A nomogram is a two-dimensional alignment scale that determines Richter magnitude based on event distance and intensity of local vibration.

[3] Affective items drawn from the Test of Science-Related Attitudes (Fraser, 1981), e.g., "I would rather find out why something happens by doing an experiment than by being told."

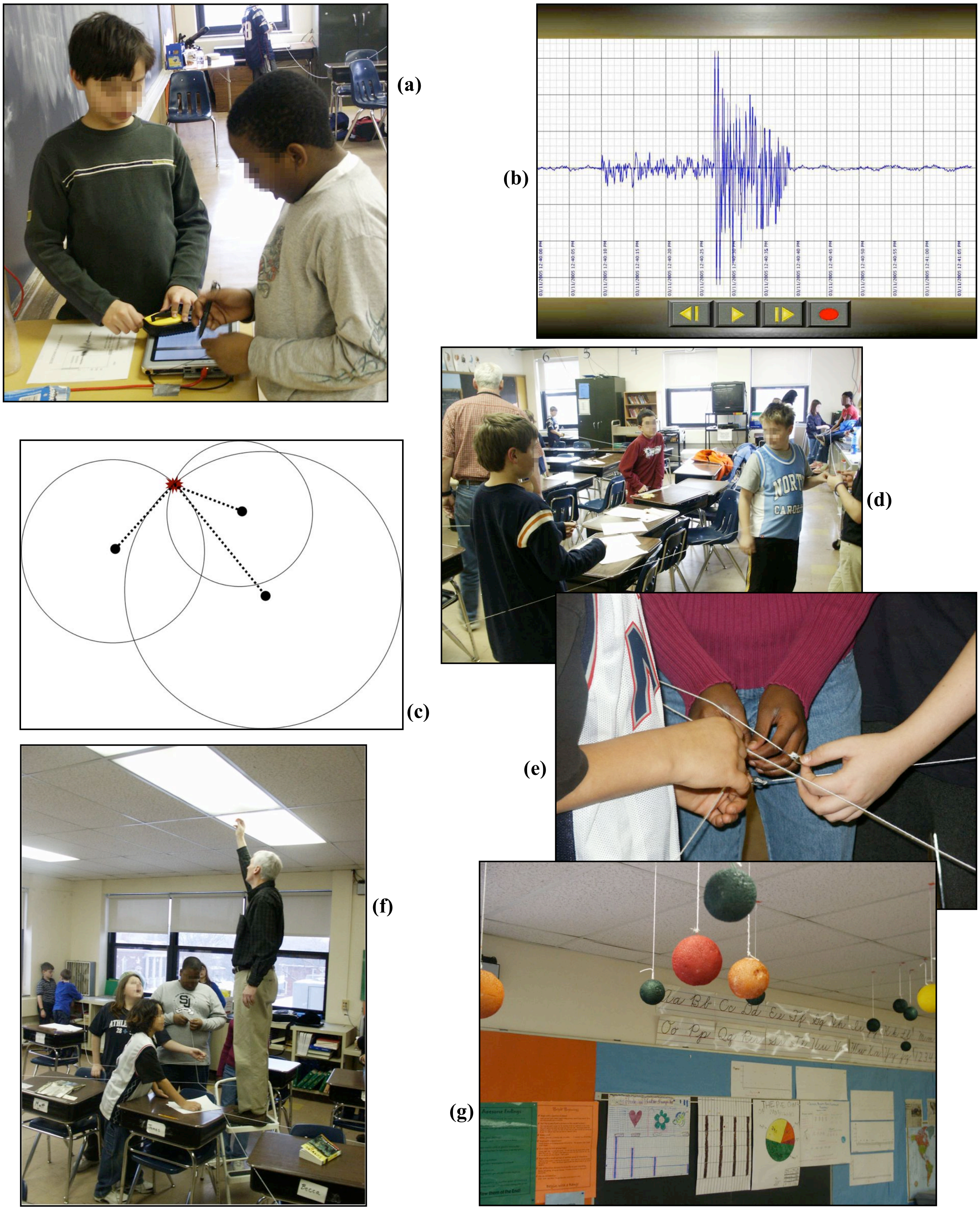

Figure 1. In RoomQuake, students use tablet computers (a) to read simulated seismograms (b) to determine event distances and magnitudes. Trilateration of event epicenters (c) are obtained by pulling calibrated dry-lines (d) from multiple seismographs until they converge (e). Color-coded Styrofoam balls are hung from the ceiling (f) to mark event epicenter and magnitude. Over weeks, the collection of markers reveals the fault line in the classroom; students maintain posters showing the emerging data (g).

As in RoomQuake, the instructional challenge to groups of students was first to engage in careful observation and reporting of activity, and secondly to engage in group discussions about the observed data. In this case the purpose of the group discussion activity was to propose experiments to determine the set of local conditions that would attract desirable insects while driving out the pests. Students were responsible for filling out paper-based “Environmental Action Requests,” complete with justifications, prior to effecting variable changes. The newspaper provided qualitative feedback on the impact of students' experimental manipulations; this was used to complement quantitative data obtained by students introducing changes in pesticides and moisture content and observing the effect on bug populations over time (Figure 3).

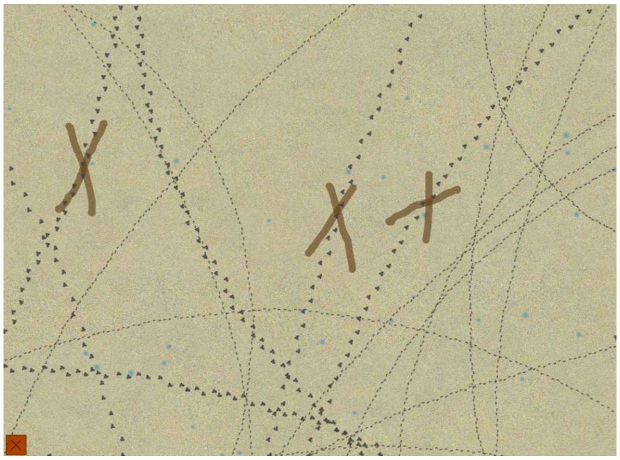

Figure 2. RoomBugs interface showing simulated tracks of insects and the presence of pesticide (small dots). Students identify and count tracks to obtain local infestation estimates. The interfaces are presented on horizontally oriented tablet computers. The X's were marked (using a stylus) by users to designate tracks already counted.

Figure 3. Using sticky dots on large posters, students maintain historical representations of bug populations found in their regions in an effort to discover local conditions that attract desirable bugs and repel pests.

Students showed remarkable work accuracy, correctly identifying almost 95% of over 1500 insect tracks. Students' ability to design and conduct meaningful experiments by imposing experimental control improved over the course of the unit, with a marked decrease in the frequency of manipulations that involved simultaneous changes in two independent variables. However, student ability to articulate a multivariate control strategy on a transfer test, while trending in the positive direction, did not show significant gains from pre- to post-tests. As with RoomQuake, attitudinal changes toward personally developed evidence were significant before and after the unit (Barron *et al.*, 2006).

HelioRoom. HelioRoom is a visual simulation of the orbital motion of the planets in the Solar system. In our implementation, a tablet computer is Velcroed to the middle of each of the four walls of a classroom. Adopting the pretense that the Sun is coincident with the center of the room, the tablet computers become synchronized viewports into the Solar system, with the planets revolving 360º around the periphery, temporarily entering a viewport, then leaving and becoming invisible for a while, then entering the next viewport, and so on. HelioRoom presents a greatly simplified model of the Solar system. The Solar system is reduced from ratio to ordinal scale; the order of the planets is maintained, but the distances among them are not proportional to their actual distances from the Sun. Orbital periods are reduced proportionately. Size and surface features are intentionally ignored; each planet is represented only as a uniform size sphere of a distinct color. The overall illusion is of colored discs traveling in a counter-clockwise fashion at different speeds, with some discs crossing in front of other discs as they overtake them (Figure 4).

HelioRoom has been used in classes ranging from third through eighth grade, in the context of instructional designs intended to promote development evidence-based argumentation, experimenting with several different scaffolding strategies for organizing large collections of observations into forms that facilitate retrieval in argument construction. While that strategy has proven only marginally effective to date (Thompson & Moher, 2006) in promoting argument development, we are continuing to refine the instructional strategy. HelioRoom did prove effective in improving eighth graders' knowledge of planetary order and, more importantly, the relationships among orbital period, angular velocity, and distance from the Sun.

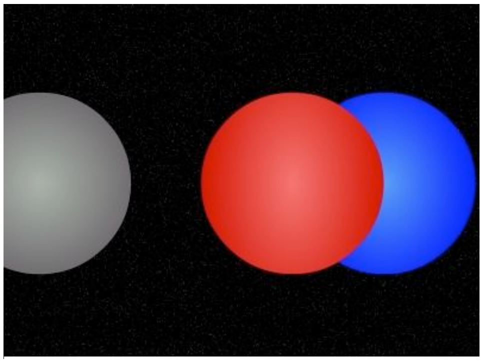

Figure 4. HelioRoom display.

Motivating Embedded Phenomena: the use of classroom time and space

Classroom space. A central component of our framework is the conceit that the phenomenon under investigation is unfolding within the confines of the classroom itself. This is not an obvious choice, nor necessarily the correct one. When studying seismology, for example, many learning researchers would argue that authenticity demands that the discourse be situated in a scientifically accurate geographic framing; we should be talking about earthquakes around the Ring of Fire, for example. We conjecture, however, that by situating the phenomena "in here" rather than "out there" we might increase learners' emotional interest in the phenomena, and leverage incidental associations between the simulated and real worlds (e.g., "the epicenter was right over my desk," or "there are bugs crawling all along the front of the room.") Moreover, we hope that by situating the imaginary phenomena within the classroom space students can build on their accumulated knowledge of the physical, social, and cultural features of the environment as they undertake a new type of activity. While we have observed such effects, the larger question of the differential effects of these two approaches remains an area for further research.

Another feature of our approach is the decision to maximize the nominal spatial extent of imagined phenomena by scaling them (up or down) to fill the physical space of the room. From a perceptual perspective, we hope to increase the salience of the phenomena for learners (Collins *et al.*, 1991). On a more practical level, we also believe that this strategy can reduce congestion in the classroom by allowing students to use the entire floor space as they conduct their investigations.

In embedded phenomena, access to the representation of the state of phenomena is physically distributed throughout the space of the classroom. We believe that this offers three important benefits. First, it creates multiple natural contexts for students to engage in discourse with peers and teachers (Vygotsky, 1978) concerning the phenomenon. Second, it reinforces the important science concept that understanding the state of a phenomenon might not be possible from a single observation, but may require multiple probes from different vantage points that require aggregation and coordination to come to full understanding. Third, we expect that by requiring physical movement from one part of the room to another in order to obtain complementary data we might reinforce memory by associating it with a physical action (Wisneski *et al.* 1998).

A final motivation draws from a desire to physically immerse learners within the experience (Dede *et al.*, 1997); in our framework, not only are the phenomena embedded in the space, indeed the learners themselves are embedded within the phenomena. The importance of embodiment has strong advocates both in psychology (Johnson, 1987; Clancey, 1997; Clark, 1997; Glenberg, 1997, 1999; Wilson, 2002; Winn, 2003) and human-computer interaction (Dourish, 2001). Embodiment approaches argue, "thought grows from action and that activity is the engine of change" (Thelen, 1995). In this perspective, cognition arises specifically through bodily interactions with the world.

Classroom time. Schools are constantly struggling with ways to make more effective use of time, both to provide opportunities for teachers to collaborate with their peers to improve instruction and to afford students opportunities to meaningfully engage both required and supplemental curriculum content. The embedded phenomenon framework engages the issue of time along three important dimensions: duration, persistence, and pacing. In the past, embedded phenomena have been employed in units that lasted in each case for several weeks. The long time course of these deployments offers several important benefits. First, it opens the door to the study of phenomena that unfold slowly, requiring investigative processes involved in "patient science" that is unlike those used in most classroom science work. A second potential benefit lies in the value of time for students to become meaningfully involved in the enterprise of scientific investigation: different learners engage in activities at different paces. Our prior classroom experience led us to expect that while highly motivated, achievement-oriented students would readily become engaged in our activities, other students would need time to move, in Lave and Wenger's terms, from the periphery to the center of the community of scientific practice (Lave & Wenger, 1990). The persistent representation of phenomena, combined with the spatial immersion, further promotes the goal of engaging all students; for all but the most dedicated non-participant, it eventually becomes easier to participate in an activity that impinges on his or her perceptual system all the time, wherever they look, than to ignore it, particularly when respected peers are engaged in the activity. Finally, by spreading interaction with the phenomena out over multiple episodes we hope to take advantage of the potential of temporally distributed instruction over concentrated, "massed" instruction with respect to recall and motor skill development (Donovan & Radosevich, 1999; Cepeda *et al.*, 2006).

Conclusion

Embedded phenomena are just that: phenomena. They do not themselves constitute an instructional design any more than naturally existing phenomena would. But the embedded phenomena framework does affords a fundamentally new genre of activity structures, uniting themes that are at the forefront of contemporary research in the learning sciences, human-computer interaction, psychology, and education. In this paper we have described the framework, and attempted to briefly present the argument for further exploration of the framework, based on contemporary learning research, classroom realities, and preliminary empirical evidence. As we move forward, perhaps the most interesting issue is the differential contributions of temporal and spatial embedding impact learner outcomes; this is the subject of our current research.

By adopting the constraints of a hardware platform available in nearly every classroom in the nation—Internet-connected conventional computers running standard web browsers—the embedded phenomena framework has the potential for exceptionally broad near-term utilization by K-12 learners and teachers. At the same time, the approach anticipates a classroom environment infrastructure in which ambient media are as ubiquitous as today's chalkboards. Situating the research study in diverse schools increases the likelihood that the results apply broadly across learner and teacher populations. The approach brings the added benefit of permeating classrooms with science content and processes within curricular constraints that often relegate science to second-class status. The cross-fertilization among fields, reflected in the multidisciplinary project team including computer scientists, psychologists, physical scientists, and educators, portends widespread dissemination and application of project research outcomes.

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