Embedded Phenomena: Supporting Science Learning with Classroom-sized Distributed Simulations

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ABSTRACT
'Embedded phenomena' is a learning technology framework in which simulated scientific phenomena are mapped onto the physical space of classrooms. Students monitor and control the local state of the simulation through distributed media positioned around the room, gathering and aggregating evidence to solve problems or answer questions related to those phenomena. Embedded phenomena are persistent, running continuously over weeks and months, creating information channels that are temporally and physically interleaved with, but asynchronous with respect to, the regular flow of instruction. In this paper, we describe the motivations for the framework, describe classroom experiences with three embedded phenomena in the domains of seismology, insect ecology, and astronomy, and situate embedded phenomena within the context of human-computer interaction research in co-located group interfaces and learning technologies.

Author Keywords
Embedded phenomena, classroom learning, science inquiry

ACM Classification Keywords
H5 Information interfaces and presentation; K.3.1 Computer Uses in Education

INTRODUCTION
Where learning technologies were once circumscribed by the form factor of the desktop computer, emerging ubiquitous technologies are giving rise to a cornucopia of new designs that expand the space of activity structures available to students and teachers [35]. In [27], we introduced one such design space, *embedded phenomena*, intended to create opportunities for learners to explore the kind of "patient science" in which the making of meaning requires the accumulation of evidence gathered over extended periods of observation. The goals of this paper are to further develop the motivation for the embedded phenomena paradigm, to describe our experiences with three examples of embedded phenomena introduced in classrooms over the past year, and to situate the framework within the context of contemporary research in human-computer interaction and learning technology research.

The design space of the embedded phenomenon framework is characterized by four common attributes.

- Simulated scientific phenomena (in the examples given here, seismic activity, planetary motion, and insect ecology) are "mapped" onto the physical space of the classroom.
- The state of the simulation is represented through distributed media located around the classroom representing "portals" into that phenomenon depicting local state information corresponding to that mapping.
- The simulations are persistent, running and being presented continuously over extended time periods, concurrent with the regular instructional flow.
- Students monitor and manipulate of the state of the simulation through those media, collectively gathering evidence to solve a problem or answer a question.

Embedded phenomena are grounded in the principles of situated, experiential learning [25]; the learner activity at the core of embedded phenomena is scientific inquiry. In designing activities, we ask students to do the (sometimes mundane) things that practicing scientists do when conducting investigations: make observations, take measurements, record and aggregate data, look for patterns, articulate and test theories, and report and reflect on their findings. In this way, the embedded phenomena approach does not differ from traditional experience-based learning methods, with or without technology, that have always been used by teachers as an important element of science education.

It is important to point out that, in and of itself, our framework does not prescribe an instructional design *per se*, nor does it provide any direct scaffolding to support learning. Technology supporting such prescriptions and supports might be developed over time as adjuncts to the framework, but for the present, we leave these in the hands of instructional designers and practitioners. The contribution introduced by the embedded phenomena framework lies in the way that phenomena are made accessible and responsive to the needs of learners [37] through the novel uses of classroom time and space.

MOTIVATING EMBEDDED PHENOMENA

Leveraging 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 [7]. 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. Our strongest motivation, however, draws from a desire to physically immerse learners within the experience [10]; in our framework, not only are the phenomena embedded in the space, indeed the learners themselves are embedded within the phenomena.

In embedded phenomena, access to the representation of the state of phenomena is physically distributed throughout the space of the classroom. We believed that this offers four important benefits. First, it creates multiple natural contexts for students to engage in discourse with peers and teachers [43] 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 [46]. Not incidentally, this arrangement of media gives children a sanctioned outlet for physical activity.

Leveraging Time

Time, more than space or funding, is the most precious commodity in schools. 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 two important dimensions: duration and persistence. In the examples that we describe later in this paper, embedded phenomena were employed in units that lasted in each case for several weeks. The long time course of these deployments offers three important benefits. First, it opens the door to the study of phenomena that unfold slowly, requiring investigative processes unlike those used in most classroom science work. Second, by spreading interaction with the phenomena out over multiple episodes we hope to take advantage of the well-established superiority of temporally distributed instruction over concentrated, "massed" instruction with respect to long-term memory and skill development [12]. But we believe that the more important motivation lies in the value of time for students to become meaningfully involved in the enterprise of scientific investigation: different learners engage 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 [25]. 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.

Persistence brings at least three additional benefits. First, by continually representing phenomena, we create the opportunity to reinforce the concept that, in nature, important state changes are not always synchronized to fixed schedules, that "things happen when they happen," and that scientists (particularly in observational sciences) are often at the mercy of events rather than the other way around. Second, persistence provides opportunities for "incidental" learning in much the same way that foreign vocabulary words adorning classroom walls may result in learning without explicit reference during formal instruction. We argue that the role of "student in the classroom" inherently demands the ability to attend to multiple concurrent threads of activity; at the same time that a teacher is speaking, a student might be working on a laboratory project, avoiding a spit-wad propelled in their direction, tracking the progress of a playground basketball game visible through the classroom window, and receiving an oral invitation to an after-school event from the student at the next desk. By adding an attentional channel that promotes curricular goals, we address the human need for variety and offer a potentially productive alternative to the normative instructional flow. Finally, by interleaving salient simulations with regular instruction, we surreptitiously expand students' opportunities to engage science content, which, at least in the United States, is often given short shrift in formal instructional schedules because of the exigency of reading and mathematics instruction to accommodate high-stakes performance assessments.

EMBEDDED PHENOMENA IN THE CLASSROOM

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 they cross the sandbox, they leave characteristic tracks that vary depending on species (Figure 1). By consulting an accompanying "field guide," users can 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.

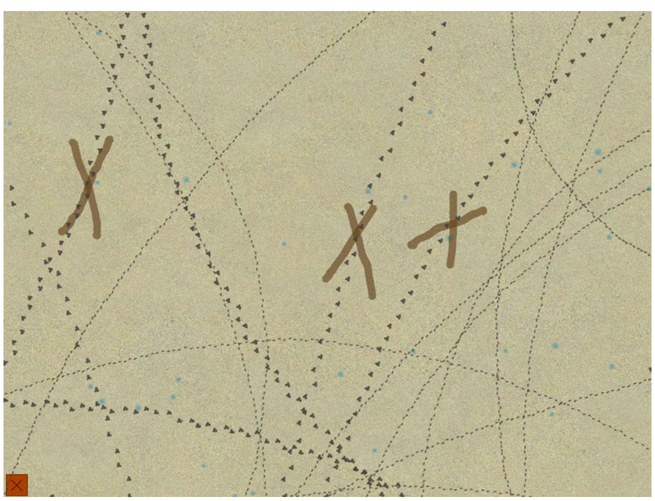

Figure 1. RoomBugs interface showing simulated tracks of insects and the presence of pesticide (small dots). Students identify and count tracks to obtain local infestation estimates. The interface is presented on a horizontally oriented tablet computer. The X's were marked by users with a stylus to indicate paths already counted.

In conjunction with a three-week unit on animal ecologies, we deployed four networked "sandboxes" in different locations within a sixth-grade classroom (ages 11-12 years). 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 unrepresented intermediary regions).

The instructional challenge to groups of students was to experimentally determine the set of local conditions that would attract desirable insects while driving out the pests. 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. The newspaper provided qualitative feedback on the impact of students' experimental manipulations; this was used to complement quantitative data obtained by systematically introducing changes in pesticides and moisture content and observing the effect on bug populations over time (Figure 2).

Figure 2. 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.

A comparison of simulation logs with student data representations showed remarkable work accuracy, with students 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 multi-variate control strategy, while trending in the positive direction, did not show significant gains from pre- to post-tests.

HelioRoom

HelioRoom simulates the movement of the planets, adopting the conceit that the center of the classroom coincides with the center of the Solar system: the Sun. Using Velcro, networked tablet computers are affixed to the walls of the classroom; each display represents a "view-port" providing a radial perspective from which to observe planetary motion. As the planets orbit around the Sun, they pass through the viewports, temporarily disappear as they travel through interstices between displays, then reappear in the next view-port, along a counter-clockwise path.

HelioRoom is intended for use in lower elementary grades as a follow-on activity to an introductory unit on the Solar system. The typical content of such units includes the principle of heliocentrism, along with the order, size, and orbital periods of the planets. Ordinarily, this represents "tacit" knowledge for young learners: a set of facts without immediate applicability. HelioRoom is designed to provide an environment within which new knowledge about the order and relative orbital periods of the planets may be reinforced by applying it in a problem-solving context [5].

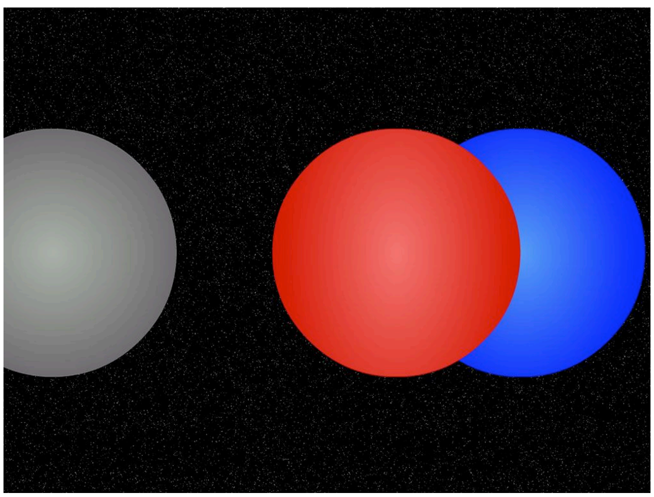

Figure 3. Colored circles represent the planets of the Solar system passing through a HelioRoom view-port. Visual cues regarding planet size, distance, and surface features are intentionally ignored; students determine planets' identities based on occlusion and relative orbital periods.

In support of those learning goals, HelioRoom takes several liberties. The planets are presumed to orbit along strictly planar, circular paths. The depiction of the planets as they pass through the view-ports ignores visual differences owing to distances, size, or surface features; all of the planets are represented by uniform-sized solid circles of different colors (Figure 3). (Common color associations, e.g., red Mars or green Earth, were intentionally avoided.) The orbital periods of the planets are shortened, but proportional consistency is maintained.

The instructional challenge to the students is to determine which color has been used to represent each planet. In order to accomplish this task, they must utilize information gained from observation within two evidentiary systems; the relative order of the planets as indicated by occlusions as one planet passes in front of another, and the relative orbital speeds of the planets (Figure 4).

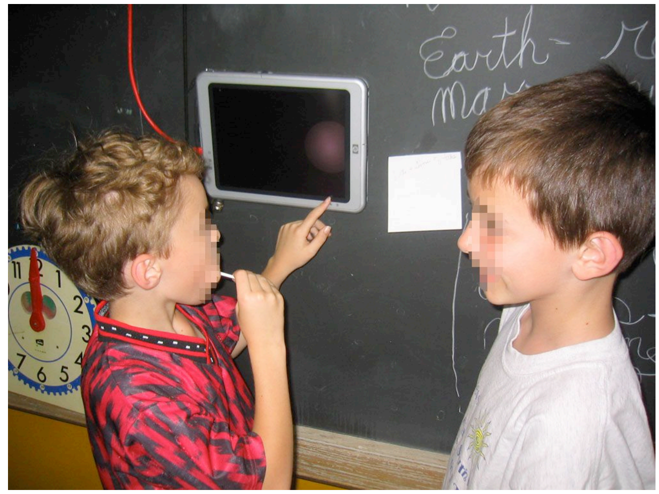

Figure 4. HelioRoom view-port represented on tablet computer affixed to classroom wall. Students observe planets as they pass through the view-port on their orbits.

In May 2005, HelioRoom was used for a 12-day period in a third-grade (ages 8-9 years) classroom that had previously completed the basic Solar system unit. Orbital periods were set in such a way that Mercury required eight minutes to complete a full orbit, resulting in an orbital period for Pluto of almost six full days. The simulation was left running at all times. Adopting the classroom teacher's standard practice of publicly representing emerging knowledge on a classroom "Idea Board" students used note cards to record and post their observations of planetary occlusions and relative orbital periods, along with assertions about planetary identities (Figure 5). Periodically over the trial the students and teacher would gather at the Idea Board to discuss their current theories and attempt to reach consensus on the identity of the planets.

Within one minute of the introduction of the activity, students had identified Mercury by virtue of its very short orbital period. Progress in identifying other planets came more slowly, but by the end of the 12-day trial, students had reached a consensus and successfully identified six of the nine planets. Not surprisingly, the six planets identified were those closest to the Sun, with the shortest orbital periods, reflecting the need for qualitatively different strategies for observing planets that moved too slowly to compare relative speeds, or in which pair-wise occlusion occurred rarely or outside of classroom time.

While students used both occlusion and orbital periods as the basis for their investigation, analysis of student note cards revealed a somewhat surprising result. By approximately a 3:2 ratio, students based their theories on observations of orbital periods and planetary speeds rather than occlusions; we had expected (qualitative) occlusion to dominate observations. One small group of students surprised us by accurately calculating the multiplicative "speed-up factor" of the simulation relative to actual planetary orbital periods.

Figure 5. HelioRoom: Student and teacher discussing note cards containing observations of occlusions and orbital periods and theories of planetary identities on classroom "Idea Board."

An orthogonal analysis of the note cards focusing on evidentiary reasoning showed a dominance of theory articulation over recording of observations, and an even split between unsupported and evidence-based theories. It became clear that the large number of note cards (128 were posted on the Idea Board) focusing on pair-wise comparisons of planets became too difficult to use in constructing arguments that required the application of transitivity.

RoomQuake

Our most mature example of the embedded phenomenon model is RoomQuake, an earthquake simulation system. Students 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. Ambient media 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 (emanating 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 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. Over the course of about two dozen earthquakes spread over six weeks, the classroom "fault line" emerges. Figure 6 illustrates the complete process.

RoomQuake has undergone two extended trials in fifth grade (ages 10-11 years), with an intervening design revision. In the first implementation, PocketPCs were used to simulate the seismographs; their size, however, limited visibility, and they were replaced with tablet computers for the second trial. In addition, the second version of the system added a data-entry form for manually recording event parameters through the ambient media.

In both trials, extensive formative and summative testing was used to assess student learning in the areas of seismological practice (i.e., the ability to read and interpret seismograms and to determine event epicenters through trilateration) and students' conceptual understanding of the spatial, intensity, and temporal distributions of seismic event series.

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 demonstrate the process of trilateration, translating that physical 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.

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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-dimension alignment scale that determines Richter magnitude based on event distance and intensity of local vibration.

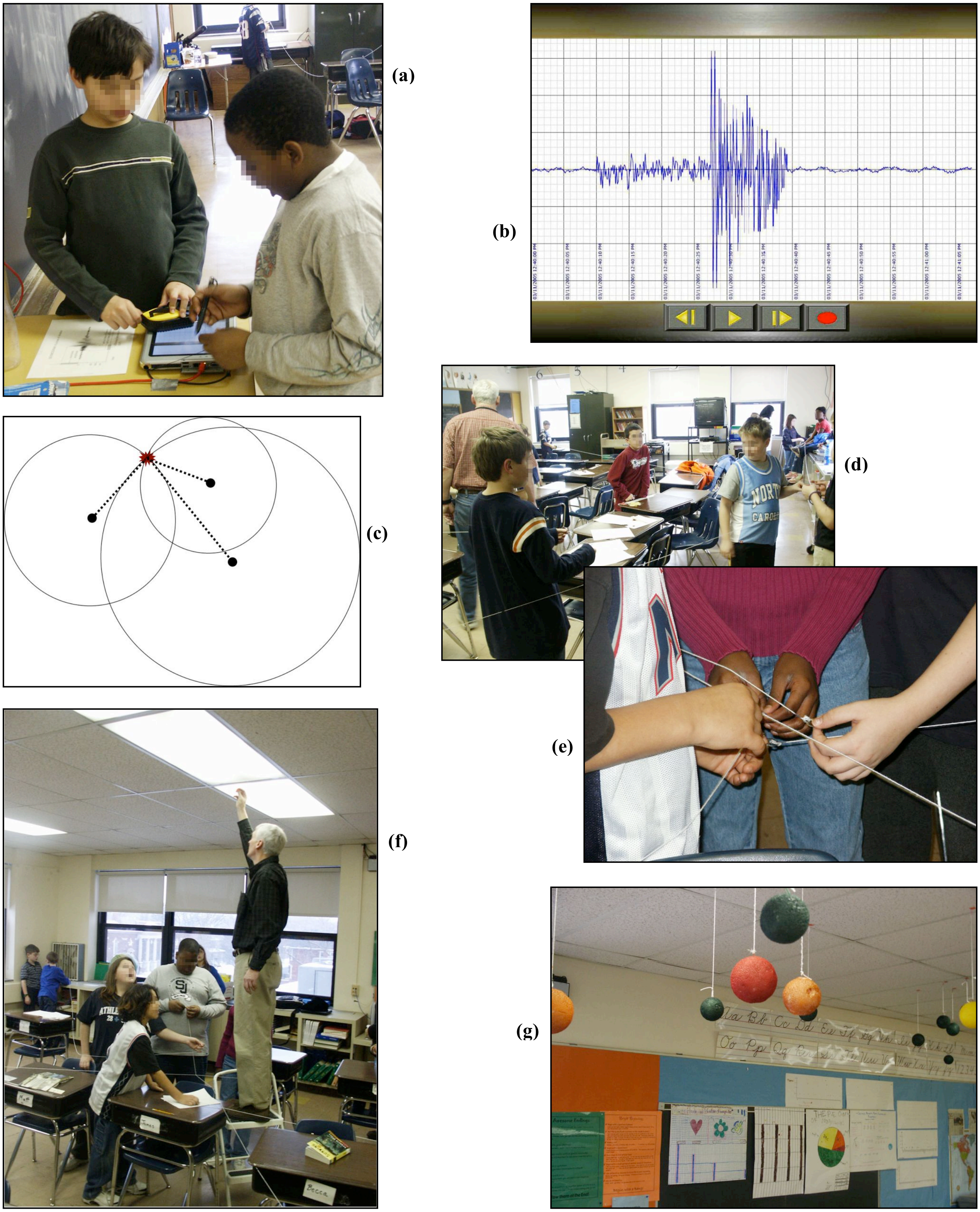

Figure 6. In RoomQuake, students use tablet computers (a) to read simulated seismograms (b) to determine event distances and magnitudes. Trilateration of event epicenters (c) are obtained by pulling calibrated dry-lines (d) from multiple seismographs until they converge (e). Color-coded Styrofoam balls 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 poster representations of emerging data (g).

DISCUSSION

While the presentations above provide tentative evidence of learning impacts, a number of additional crosscutting issues have emerged from our classroom experiences with embedded phenomena. We focus briefly on four of those in the following: instructional context, participation, scalability, and affective impact on learners.

Instructional context

In some ways embedded phenomena are nothing more than "plug-compatible" substitutes for natural phenomena. They do not prescribe specific instructional sequences or materials, but rather demand design, adaptation, and scaffolding by practitioners. In our work, our collaborating teachers have been critical partners in helping us to explore instructional contexts. Among their many contributions, we believe that two have to be especially important lessons that will inform our ongoing work.

The first of these is the need to keep the ongoing products of student work as visible as the phenomena themselves [7]. In the first deployment of RoomQuake, for example, the historical record of seismic events was available by scrolling through history on the individual PDAs, but no public record was accumulated until the summative activities at the end of the unit. The introduction of large posters in subsequent classroom embedded phenomena units helped to maintain the "thread" of the ongoing activity and keep attention focused on the accumulating empirical evidence.

The second contribution was recognizing the importance of teachers' knowledge of individual students, and how their activity should be organized and coordinated within the social fabric of the class. Teachers were able to balance choice and responsibility, ensure productive team partnerships, and opportunistically engage in whole class and individual scaffolding that were essential to the learning process.

Participation

In the second RoomQuake pilot, we instrumented the classroom with six cameras, capturing and coding the participation of each student in the various roles (seismogram reader, dry-line holder, measurer, data recorder, etc.) for each of 21 simulated seismic events. We found striking individual differences in both the rate and variety of participation in various roles, ranging from students who maintained a consistent rate throughout the unit, to those who were active participants at first but appeared to lose interest over time, and finally to students who didn't begin to actively participate until long into the series of earthquakes. Similar participation variability was evidenced in the distribution of note card authors in the HelioRoom unit, and anecdotally observed in RoomBugs.

While we were heartened to see that the long time course of RoomQuake provided an opportunity for "disengaged" students to move, in Lave and Wenger's terms, from the periphery to the center of a community of practice [25], the response variability suggests that instructional decisions surrounding the duration of embedded phenomena and the articulation of standards for participation require careful planning with attention to classroom populations.

Affective impact

Brief interventions and point-based assessments do not necessarily provide a rich picture of the impact of experiences on learners. While we saw positive short-term learning effects, we do not expect that a significant number of the students with whom we work to pursue careers as practicing scientists. Our larger goal is simply to promote a science-literate populace by establishing a propensity toward evidence-based reasoning and empowering learners to believe in themselves as legitimatized observers of phenomena. In the RoomBugs and (second) RoomQuake units, we administered a Likert-scale affective test based on the Test of Science-Related Attitudes (TOSRA) [16]. In both cases, students showed substantial positive movement on items such as "I would rather find out why something happens by doing an experiment than by being told" and "I would rather do my own experiments instead of finding something out from a teacher." On a cautionary note, the most significant affective change in the RoomQuake unit was stronger agreement with the statement "Being a scientist takes too much work."

Scalability

The embedded phenomena described in this paper require only modest technologies. While it would not be difficult to imagine complementing each of these activities with richer affordances (e.g., personal computational devices to record data, position tracking to personalize views, etc.), we made the intentional choice to limit our technology choices to those that were similar to what we could already find in classrooms. Each of these embedded phenomena are delivered at the client end on conventional web browsers containing Flash plug-ins, served by an Apache web server running on a personal computer housed in our laboratory. The minimal computational and communication demands imposed by these simple applications raise the possibility of the emergence of a class of "phenomenon servers" that could economically deliver simulated science phenomena to large numbers of classrooms, using conventional classroom computers as ambient media clients.

RELATED WORK

Interaction

From an interaction perspective, embedded phenomena support the collaborative activity of workgroups through the use of multiple media devices distributed within a single physical space, a common deployment framework in CSCW and CSCL research. Kraemer and King [24] surveyed a number of the early efforts in this area, which were typically configured as a fixed collection of private workstations in combination with a large public displays within an "electronic boardroom." Systems such as Xerox PARC's Colab [38], the University of Arizona's Planning Laboratory [2], and the Microelectronics and Computer Technology Corporation's Project NICK [4], and their successors, have focused on support for activities such brainstorming, decision support, and planning within group meetings. Among instructional systems, ClassTalk [14], eClass (formerly Classroom 2000) [1], ActiveClass [32], LiveNotes [21], and HubCalc [45] share a similar mix of private and public media (albeit with wireless computational devices increasingly replacing dedicated private workstations).

While these systems are designed to support group activity in fairly structured settings in which participants are focused on a shared goal during a fixed time period, more recent systems, such as MessyBoard [15], Notification Collage [17], and Semi-Public Displays [19], among others, have explored the utility of embedded devices for opportunistic interaction within co-located work groups engaged in longer-term collaborative activity. 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 [39] in which all interaction is undertaken publicly on shared devices. And while they share with 'roomware' projects such as iRoom [20] and i-LAND [40] 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 [18], but rather as a means of distributing the representation of state over physical space, requiring users to attend to multiple devices in order to understand and/or control the state of the ongoing simulation.

Like ambient displays [47], embedded phenomena are designed to provide representations of persistent, dynamic phenomena. Although ambient media are often associated with non-display-based *fixtures* [47], 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" [26] 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 display data 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") [36]. 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 peacefully co-exist in time and space.

Learning technologies

There is a rich tradition of employing simulations in support of science inquiry learning through a variety of media including desktop-based microworlds [e.g., 11, 28], first-person virtual environments [e.g., 3, 9], and distributed handheld devices [e.g., 8, 42][3]. Simulations increase the space of accessible phenomena and afford the introduction of simplifying abstractions that scaffold learning. Embedded phenomena draw special inspiration from pioneering simulation systems that enable students to serve roles [33] as embodied participants [13] engaged in the enterprise of authentic scientific investigation, particularly the concept of participatory simulations [6, 44].

In recent years, several researchers have begun to employ embedded ubiquitous computing media to support science learning [29, 34]. Two pioneering projects emanating from the U.K. Equator project bear special relevance. In the Hunting of the Snark [30], 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 are provided to allow children to explore Snark characteristics in multiple modes of activity. In the Ambient Wood projects [31], probes are used in conjunction with fixed-location "kiosks" that serve as complementary data sources. In Environmental Detectives [23], activities situated in outdoor spaces are augmented with PDAs that provide simulated data on environmental parameters. 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.

CONCLUSION

The euphoria surrounding the introduction of computers and schools, and the inevitable backlash when they did not prove to be panaceas, has given way to a more principled exploration of the affordances that technologies might provide [37]. We are beginning to see the fruits of a more

[3] There is a similar rich literature in the area of student modeling and authoring of simulations dating back to the Apple Vivarium project [22]; embedded phenomena contrasts with this work in its exclusive use of pre-built simulations.

disciplined approach that is moving learning technologies beyond simple toy systems into tools that make a demonstrable difference [e.g., 41] for learners and teachers.

In this paper, we have sought to add to the practitioner's toolbox by introducing a new way to use existing technologies, *embedded phenomena*, which addresses the needs of learners while making innovative use of classroom space and time. We showed that the framework is sufficiently flexible to manifest a broad range of curricular phenomena. Our classroom experiences provide support for the assertion that the use of embedded phenomena can impact student learning, participation, skill acquisition, and attitudes toward the scientific enterprise. Finally, we showed how the essential elements of the framework have been informed by research in human-computer interaction and learning technologies.

When describing embedded phenomena to people for the first time, we have found that once they understand the basic idea they are quickly able to suggest ideas for the representation of new phenomena. We hope that the our framework will spur refinements and extensions that expand learners' opportunities to engage in the practice of science.

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