WallCology: Designing Interaction Affordances for Learner Engagement in Authentic Science Inquiry

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ABSTRACT

The broadening array of technologies available to support the design of classroom activity has the potential to reshape science learning in schools. This paper presents a ubiquitous computing application, WallCology, which situates a virtual ecosystem within the unseen space of classroom walls, presenting affordances for science learners to engage in investigations of ecological phenomena. Motivated by a desire to foster authenticity in classroom science inquiry, WallCology extends the "embedded phenomena" framework in three ways: by enabling collaborative investigations among distributed work teams, by increasing the physicality of investigation activities, and by expanding the loci of activity sites. Pilot studies in two urban classrooms provide qualified support for the effectiveness of WallCology in promoting more authentic inquiry practices, content learning, and attitudes regarding scientific investigations.

Author Keywords
Embedded phenomena, ubiquitous computing, science inquiry learning.

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

INTRODUCTION

The canonical "scientific method" that many of us learned in school—hypothesis, experiment, and conclusion—captures only a small fraction activities enacted within the practice of working scientists [10]. Modern conceptions of science inquiry recognize activities such as observation, the use of instrumentation, selecting and controlling variables, argumentation, division of labor, and communicating results, as components of the broad range of empirical investigations of phenomena. Chinn and Malhotra [6] provide a compelling study of the ways in which instructional units of all kinds (with or without the use of computer-based technologies) generally fall short of the ideal of realistic investigations. Contrasting "authentic inquiry" with "simple inquiry," they identify a rich set of cognitive processes and epistemological dimensions that distinguish what usually happens in school from what happens in the laboratory or the field. The common thread running through these differences is the extent to which learners are shielded or prevented from engaging in activities that would be necessary in authentic scientific investigations, resulting in an overly simplistic view of the nature of science inquiry. This is not to say that school-based inquiry always can or even should reflect the full complexity or employ the tools of mature scientific investigations [28,34]. But while achieving authenticity in Chinn and Malhotra's sense presents daunting challenges in materials and instructional design, their critique is instructive in sensitizing designers both to the dangers of oversimplification and the opportunities for incorporating design features that extend activity in scientifically realistic ways.

In this paper, we present the design rationale and classroom experience surrounding a ubiquitous computing application, *WallCology*, intended to promote learners understandings of scientific inquiry engaged in the investigation of population ecologies. The presentation focuses on three extensions to the "embedded phenomena" framework described in [23], extensions directed toward enabling collaborative investigations among distributed work teams, increasing the physicality of investigation activities, and expanding the loci of activity sites. In each case, the extension is motivated by a desire to *problematize* inquiry in ways that demand learner activity more reflective of the decisions and tasks associated with authentic scientific practice [6, 30]. The extensions are not designed to make the students' tasks easier, but instead reflect Rogers' call for broadening the scope of the ubiquitous computing paradigm beyond Weiser's conception of "calm computing" [39] and an emphasis on proactive computing [35] through interaction affordances "designed not to do things for people but to engage them more actively in what they currently do" [31].

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EMBEDDED PHENOMENA

WallCology extends the "embedded phenomena" representational framework [3,23,37] in which dynamic animated simulations are depicted as occurring within the physical space of the classroom, rather than within the confines of a single display. Under the control of a centralized server, a collection of distributed client computers (running conventional browsers) is used as a shared interface by the entire class, rather than by individual students, with each client "portal" displaying only a partial, location-specific view of the phenomenon under investigation. Within this framework, investigations are conducted as embodied, collaborative, extended (multi-week) whole-class endeavors.

While the embedded phenomena framework draws from a broad range of human-computer interaction research (see [23] for an extended account), it can be compactly characterized as the application of ambient media [39,42] to support embodied interaction [9] around the domain of scientific inquiry. From a cognitive psychology perspective, the embodiment approach argues that "thought grows from action and that activity is the engine of change" [36]. In this perspective, cognition arises specifically through bodily interactions with the world. Learning that pairs action and knowledge, or engagement in goal-directed actions, is viewed as necessary for higher cognitive capacities of thought and understanding to develop [7,8,17,41]. The pedagogical basis for the approach derives from theories of situated learning [4,14,32]. The embedded phenomena framework situates communities of practice [40] (in this case, intact self-contained classes) within authentic activity structures (scientific investigations) for the purpose of socially constructing knowledge of both science concepts and the processes of science as a technical and human endeavor [10].

Three embedded phenomena applications designed for and deployed in elementary and middle school classrooms are presented in [23]: RoomQuake (a simulation of a series of earthquakes using simulated seismographs), RoomBugs (a simulation of insect migration and control, using horizontal tablet computers to depict insect tracks), and HelioRoom (a heliocentric solar system simulation using computers as viewports into revolving planets).

While these applications support a rich set of inquiry activities, it is possible to identify at least three facets of authentic inquiry that were not afforded within their design: (1) the opportunities and challenges related to collaboration among remote work groups, (2) the constraints and adaptations associated with the physical acts of observing and interacting with highly dynamic phenomena, and (3) the scientific demands imposed by the need to actively select from among a large space of potential points of observation in the investigation of phenomena. In WallCology, we introduce cost-effective extensions to the embedded phenomena framework that afford learners the opportunity to explore experience this richer inquiry space.

WALLCOLOGY

WallCology is a computer simulation designed to support elementary and middle school curricular goals in life science and population ecology. WallCology situates students within a complex virtual ecosystem, where they may conduct investigations focusing on topics such as the identification and classification of species, habitat selection, population estimation, food chains, predator-prey relationships, life cycle phases, adaptation, and response to environmental change. Multiple tablet computers adjacent to the walls of classrooms serve as viewports ("WallScopes") into an imaginary space inside the walls filled with the virtual fauna (Figure 1). Through the WallScopes, students see distinctive local virtual environments containing pipes, lath, and animated creatures of various species reflecting distinguishing morphologies, movement behaviors, and habitat preferences. The simulation runs continuously, concurrent with regular classroom day-to-day activities, but becomes the center of attention as inquiry activities, such as the building of field guides based on observations of phenomena or collectively estimating populations, are undertaken by the students.

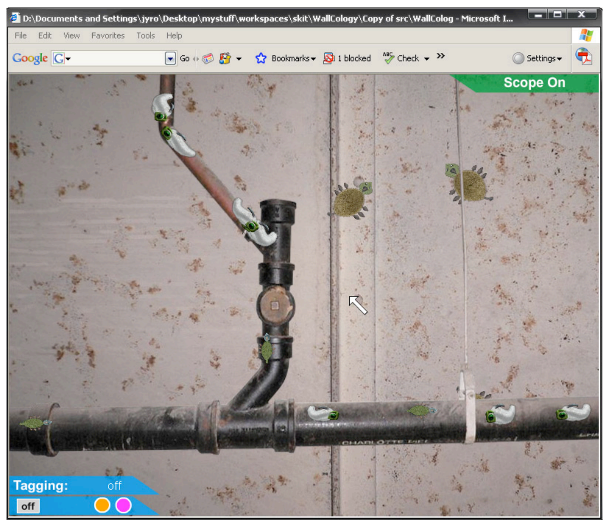


Figure 1: WallCology WallScope, with creatures crawling on the pipes and back wall.

Since the mobile populations are presumed to occupy the entire wall rather than just the portion visible through the WallScopes, creatures move in and out of the displays on a frequent basis. The modeling of creature movement employs a hierarchical architecture that distributes the computational load between the server and client. The server maintains a low-resolution representation of the location of individual creatures, with each cell in the model corresponding to a (potential) WallScope display site. A server-based computational engine modeled on population dynamics and environmental factors drives the movement of creatures from cell to cell. Client WallScopes, in turn, are responsible for the determination and animation of creature movement within their associated cell. The server signals the client upon the imminent (directional) arrival or departure of a creature; in the former case, the client application instantiates a new animation, and in the latter case, it plots an exit path, informing the server when the requested creature has moved "off scope."

These design features position WallCology squarely within the family of existing embedded phenomena applications [23]. In the following sections, we describe extensions to that framework designed to support the inquiry challenges identified above.

DISTRIBUTED COLLABORATION

A hallmark of contemporary science inquiry is the collaboration of researchers from multiple distributed sites working around research questions associated with a common phenomenon. In fields such as astronomy and seismology, for example, groups of researchers at remote sites are necessary to locate and track the movement of phenomena; the work cannot be done by a geographically isolated team. When a single team (or single investigator) has full access to the entire phenomenon, as is the case in the embedded phenomena framework, they do not have to grapple with the component activities—establishment of common vocabulary, technology-mediated communication, calibration of observations, aggregation of evidence from remote sites, etc.—that are necessary when collaborators are not collocated [1,6,24].

The importance of such collaboration to the learning of the scientific enterprise is reflected in the growth of school-based distributed data collection efforts such as the GLOBE (Global Learning and Observations to Benefit the Environment) Program [13], which engages over 20,000 schools around the world in observation and reporting of local atmospheric, climatic, hydrological, soil, biological, and phonological conditions, and has to date collected over 16 million observations by student participants. While such programs do not attempt to address the full range of challenges associated with remote collaboration, they do involve learners in authentic investigations, and highlight the benefits of wide-scale collaboration in the investigation of natural phenomena.

The use of distributed collaborative inquiry learning activities surrounding investigation of simulated phenomena has also been explored, particularly in the context of multi-user educational games. Applications such as Quest Atlantis [2], which engages distributed learners in collaborative quests designed to address environmental and social problems on a mythical world, and River City [25], in which networked collaborators plan and conduct investigations designed to uncover the causes of health problems in a 19th century town, represent environments within which learners require and learn to develop proficiency with many of the component skills of distributed collaboration.

One distinguishing feature between these two modes of inquiry is the relationship between the spatial distribution of the phenomena and the loci of investigation. In the large collaborative physical data collection projects, learners are typically responsible for data collection within a circumscribed region, such as their schoolyard or neighborhood. While this approach facilitates local control and imposes demands to aggregate and extrapolate data sets, it does not directly provide learners with opportunities to experience situations involving discrepancies arising over contrasting observations of the same phenomena. In contrast, in distributed simulations applications, learners are typically situated within a shared virtual environment, requiring resolution of observational discrepancies of the common phenomena. However, the "shared virtual environment" approach used in most distributed simulations is problematic within the embedded phenomena framework, as it violates the "locality" principle, the conceit that the phenomenon is unfolding exclusively within the bounds of the local physical environment.

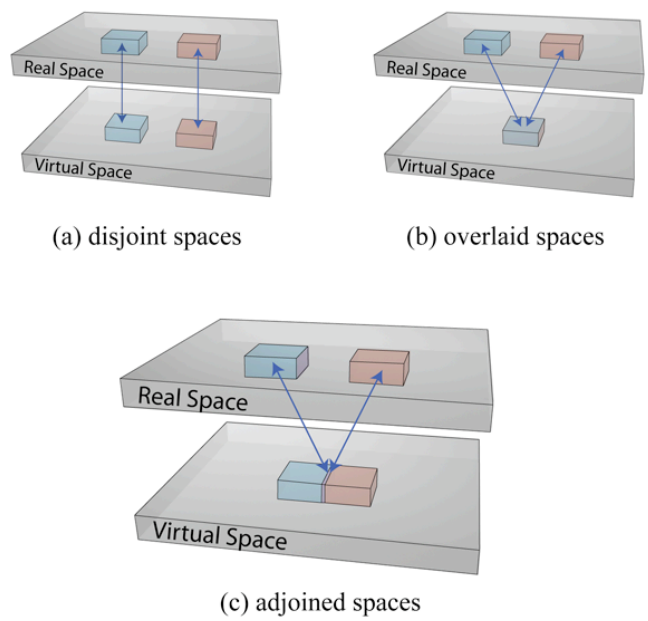


Figure 2. Distributed investigations of science phenomena. In disjoint investigations (a), multiple teams explore discrete, separated regions of a larger phenomenon. In overlaid spaces (b), multiple teams investigate the same (virtual) region. In adjoined spaces (c), multiple teams explore distinct regions with a shared boundary. (The extent of the investigated phenomena is indicated by gray shading; in (b) and (c), the entire phenomenal space is "covered" by the multiple teams.)

An approach that combines the "shared phenomena" feature of distributed simulations with the "local discrete space" of physical data collection is to make phenomena available to multiple teams along a shared boundary. Such "adjoined spaces" (Figure 2) maintain the locality of classroom-based phenomena while problematizing the coordination of observation among distributed teams.

Conceptually, the "adjoined spaces" approach sits somewhere near the intersection of shared virtual environments and augmented reality, bringing together distributed participants to act within partially shared physical environment. WallCology utilizes the adjoined spaces model by allowing classrooms to share physical or virtual walls and the populations that they inhabit. Cells contained in the server-side state model can be mapped to arbitrary clients, independent of their physical position. By assigning clients in different rooms to the same "virtual wall," students in multiple classrooms (physically or virtually "adjacent") gain access to portals into the shared virtual environment and populations within that wall (Figure 3).

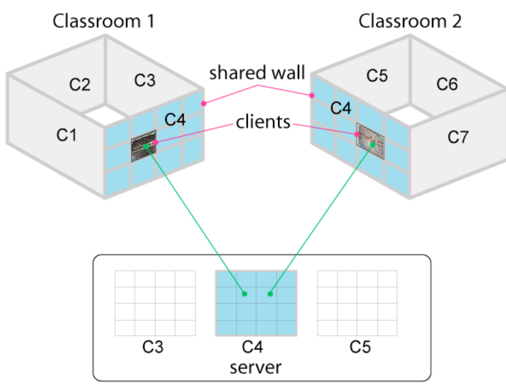


Figure 3: Adjoined spaces. Virtual wall C4 is shared between two classrooms, supporting collaborative investigation.

Maintaining the illusion of access to shared phenomena is reinforced by requiring that each server cell map to no more than a single client WallScope. (While the hierchical simulation architecture of WallCology guarantees that the populations observed in shared portals would be identical, the exact location of animated creatures would vary, since each client computer is responsible for local locomotion simulation. This potential discrepancy could be obviated by eliminating the two-tiered simulation architecture and maintaining a single model, albeit at the expense of significantly greater communication overhead.) In addition, the client WallScopes can be positioned so that they reinforce illusion of left-to-right and up-and-down flow of creatures from scope to scope. This is more important in physically adjacent classrooms, where students might have opportunities to travel between the two rooms and notice discrepancies, but is unlikely to raise fidelity issues unless students in both classes are simultaneously observing and communicating to each other dynamic character movement in real time.

"PHYSICAL" SCIENCE

While all activity is "embodied" in the broadest sense, the activities of science place numerous and varied demands on, and leverage the affordances of, the human body; chemists pour, biologists slice, astronomers squint through lenses. Where our bodies cannot support direct observation or manipulation, we depend on instruments to enhance our capabilities. When investigations center around real phenomena utilizing physical materials and tools, such as in "hands-on" science explorations or activities involving physical construction kits, the strengths and limitations of human form are explored in a natural way.

Simulations, however, can mask human limitations, and lead to experiences that lack authenticity with respect to learning the physical skills that are an important part of science inquiry. Clicking a button to effect the combining of reagents, or the wielding of a scalpel, lack the visceral challenge—or, arguably, potential for engagement—of the analogous physical acts.

In a seamless model, physical actions in the real world would have scientifically appropriate and meaningful effects in the virtual environment [16]. The world of play has good examples of such design, such as the Nintendo Wii controller, which translates arm strokes into actions on a simulated tennis ball, or in the "science" domain the Milton Bradley Operation® board game, where players are required to use tweezers to remove small "body parts" from narrow channels without triggering an electrical alarm. Such physical actions, while not identical to the skills of medical surgery, are nonetheless dependent on, and limited by, human sub-skills that arguably contribute to mature performance.

Existing learning technologies designed to explore simulated phenomena have employed "scientific physicality" in only rudimentary ways. Applications such as Ambient Wood [29] and Environmental Detectives [20], Savannah [11], MUSHI [21], and embedded phenomena [23] all require locomotion to multiple sites, supporting the scientific principle of observing phenomena from multiple perspectives. In the Hunting of the Snark [27], learners feed food phicons and use gestures to ascertain characteristics of a hidden creature. WallCology attempts to move closer to authentic physicality, while mindful of the installed technology base of classrooms.

Ephemeral Phenomena

WallCology creatures move fairly rapidly; in some cases, an individual character may only be visible within a WallScope for 10-20 seconds. For both qualitative tasks (e.g., creating a drawing of a creature for use in a student-constructed "field guide") and tasks requiring comprehensive accounts of the collective population within a WallScope (e.g., counting the number of each type of creature for population distribution estimation), the perceptual and memory demands are not insignificant. These demands mirror those that would be involved in observational studies of any rapid, mobile population, and in turn require the development of authentic skills and techniques for accommodating the characteristics of the phenomena.

Responsive Phenomena

Among small, undomesticated creatures the physical proximity of humans may raise responses such as flight, rigidity (to avoid triggering sensitive visual motion detectors), or even aggression. In WallScope, the volume level of the built-in microphones on the WallScope computers is continuously monitored and used as a presence cue that impacts the behavior of the simulated creatures. Different species exhibit characteristic but divergent responses, with some moving rapidly off the edge of the scope, others freezing in place, and still others simply ignoring the presence of the observer. Students must learn to approach the observation points quietly, and to consider the reaction to noise as a component of their behavioral descriptions of the creatures.

Portable Instruments

In situations where the limitations of the body preclude direct observation, scientists turn to instrumentation. In traditional desktop simulations (including the first prototype of WallCology), phenomena are commonly presented side-by-side with inscriptions representing dynamic state information[1]. While convenient, this approach fails to problematize three important characteristics of instrumented observation: (1) natural phenomena are not inherently accompanied by their own instrumentation, (2) the choice of instrumentation is itself a decision, based on the investigators' hypotheses concerning the relevance of multiple variables, and (3) instruments may be scarce resources that need to be shared among multiple investigators.

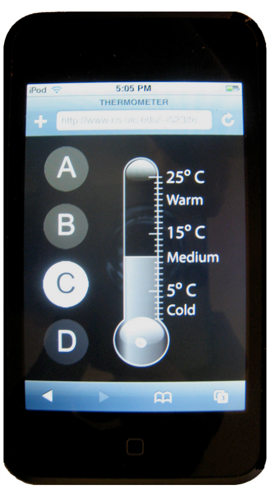


Figure 4: Simulated thermometer

In WallCology, characterization of habitat preferences and explanations of migration are dependent, in part, on the environmental variables of temperature and humidity. In the newest version of WallCology, PDAs (Figure 4) are programmed to serve as a simulated portable digital thermometer and hygrometer. State values are represented in both quantitative (e.g., ºC) and qualitative forms (e.g., Cold, Medium, Warm), both to provide a frame of reference for learners unfamiliar with the dynamic range expected within the simulated environment, and to support investigations by younger children for whom the use quantitative values demand mathematics skills beyond their experience.

Tagging

A frequent demand on scientists conducting investigations with living creatures is the use of hand-eye coordination and manual dexterity to interact with the subjects of their study. In the RoomBugs application, students used a stylus as a simulated "stick" to mark insect tracks which had already been counted, fostering the development of skill in fine-grained exhaustive population counting [3]. However, the relatively slow "decay" of insect tracks did not impose substantial demands on the pace of work.

Among the domain-focused learning goals afforded by WallCology is the development of understandings surrounding the methods by which population ecologists estimate the size of mobile populations. One general method involves a "capture-recapture" technique, in which captured creatures are "tagged," with the ratio between tagged and untagged creatures in subsequent samples providing a parameter for a population estimation formula[2].

WallCology supports a simple tagging mechanism through which learners use a stylus to "paint" a colored dot on the body of the animated creatures (Figure 5). The speed and simulated saccadic motion of some of the species used in WallCology represent a significant challenge to the tagging activity, analogous to the physical challenge inherent in capturing live creatures.

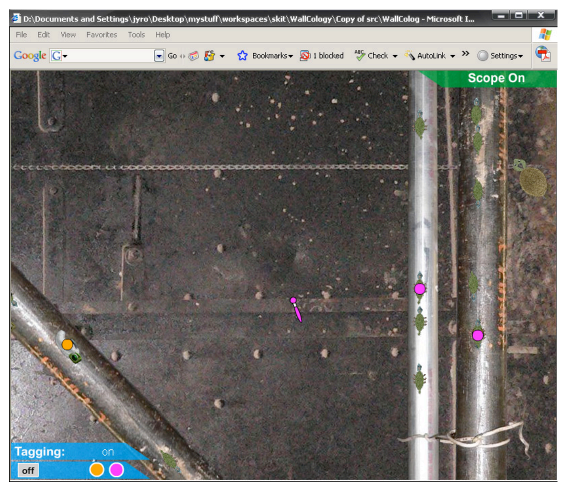


Figure 5: WallCology WallScope, showing creatures tagged with orange and pink marks.

[1] Some exceptions exist, particularly in VR-based applications. In Sandbox, for example, users select from multiple instruments and transport them to the point of observation [18]; in The Field application, PDAs are used as simulated GPS devices, external to the VR display of the simulated environment [19].

[2] The students used the Lincoln-Peterson formula $\tilde{N} = ct/r$, where $\tilde{N}$ is the estimated population, c is the number of individuals in captured in the second sample, t is the number of individuals tagged in the first sample, and r is the number of tagged individuals in the second sample [26].

GRANULARITY OF OBSERVATIONAL LOCI

An important element of authentic science inquiry revolves around the question of where to look. In medical research, for example, the underlying causes of pathologies may be located far from their surface manifestations; in astronomy, the vast extent of the phenomena raises this issue to the forefront of research planning. By fixing the position of portals, embedded phenomena remove these choices—and the learning experience that comes from having to make the choices—forcing fixed, predetermined points of access to the phenomena under investigation.

An ideal system would provide learners with an unbounded choice of places to situate observations. This has been used to innovative effect in learning applications such as Savannah [11], where handheld displays maintain continuous representation of position-dependent state information. Indoor tracking systems, based on a variety of technologies (802.11RF, RFID, camera, pressure sensors, Bluetooth, etc.), have made great strides in accuracy, capacity, and installation convenience, but issues of calibration, response latency, physical infrastructure, and cost preclude their adoption in most classrooms.

From a pedagogical perspective, it is not clear that continuous tracking is even necessary in the context of supporting authentic science inquiry. What matters is that the choice of observation points be problematized; that goal can be achieved more economically by simply creating a discrepancy between the number of available observation points and the number of devices which can be used to make observations, unlike in the embedded phenomena framework, where there is always a 1-to-1 match.

We have developed a prototype of such a capability using inexpensive iButton® technology [22]. iButtons are passive devices housed in small, round, stainless steel buttons; the simplest version contains only a silicon chip with a unique identifier. A reader attached to a communication port on a tablet computer is used to sense the identifier. By affixing a grid of iButtons to a classroom wall, we can create multiple observational sites at customized resolutions appropriate for the application (Figure 6). When the mobile "portal" attaches to the iButton, it wirelessly transmits the buttons identifier to the server, which in turn serves the information from the appropriate model cell back to the client.

This technique offers practical advantages in the classroom, as it obviates the mounting of the display, works on nearly all surfaces (and with less damage), and (for embedded phenomena applications other than WallCology) affords the positioning of observation points at locations other than the rooms' periphery. The number of observation points can easily be adjusted to accommodate the pedagogical goals of the instructional unit. In effect, the technique offers a low-cost method for providing students with a semi-continuous space of loci for interacting with the simulated phenomena.

This approach represents a major shift in the conception of the embedded phenomena framework. While the central idea behind the framework—that the phenomena are embedded within the classroom—remains in place, the portals are no longer limited to fixed locations, allowing the integration of mobile devices within the paradigm.

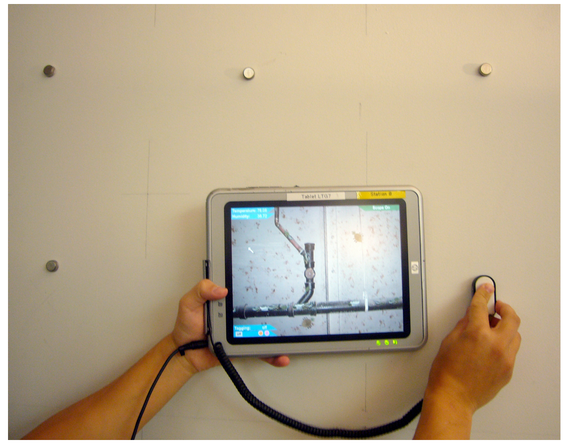


Figure 6: Mobile WallScope. iButtons affixed to walls identify user's point of observation.

EXPERIENCE

Method

WallCology has been employed in two urban classroom interventions (Figure 7); in each cases, the WallScope browser application was left running continuously for a period of about four weeks. In the first intervention, conducted in May 2007, an initial version of the application, including tagging and responsive phenomena, was used as a component of a two-month population ecology unit in a seventh grade science classroom, with tablet computers attached to walls using Velcro™. A second intervention, conducted in October/November 2007, involved a pair of adjacent third grade classrooms, utilizing a newer version of WallCology that incorporated adjoined spaces, portable instruments (in one classroom), and mobile portals (in the other classroom). In the classroom that did not employ mobile portals, large screen computers were placed on tabletops adjacent to the walls.

Figure 7: Students tagging WallCology creatures and recording observations of species distributions.

The two interventions addressed distinctive learning goals. The seventh grade unit focused on species differentiation and population estimation. Four imaginary creature types were modeled; each of two pairs of creatures was assigned similar (but not identical) morphologies, but with distinctive behavioral patterns and habitat preferences (Figure 8).[3] Students worked in small groups to create a "field guide" of WallCology creatures. Each page of the field guide asked students to sketch the creature and provide their observations of the creatures' morphologies, behaviors, and habitats. Once the field guides were completed, the teacher led whole-class discussions, eliciting theory articulation and argumentation [30] designed to reach a class consensus regarding the identification of distinct species. Population estimation focused on two techniques: static sampling and tag-recapture estimation. Students estimated WallCology populations using the static sampling method, observing the screens and noting how many creatures of each kind that they saw, then multiplying by the ratio of the wall size to the WallScope size and averaging across habitats. The process was repeated several times in conjunction with a class discussion on reliability, accuracy, and factors that could lead to inconsistent results. Student were then instructed on the tag-recapture method, and used the Wallscope tagging facility mark creatures that wandered into their WallScopes over a thirty minute period, using the Lincoln-Peterson formula to estimate the creature populations.

The third grade unit focused on issues of mobility, life cycles, adaptation, population variation, predation, and food chains. New creature models (not shown here) were constructed to reflect holometabolous insect (including egg, larva, pupa, and adult stages) and mammalian development cycles. The field guide approach was used again, this time with a stronger focus on adaptation and habitat description. Unlike the seventh grade experience, creature populations were programmed to vary over the course of the third grade unit, and students tracked population changes by counting the various creatures in their WallScopes and recording data on large wall chart graphs. In order to minimize gore, predation was limited to the consumption of eggs rather than adult creatures, which served as cues for students' determination of food chains, which they drew in their field guides. Tagging was used to study mobility rather than population estimation; each class received a set of distinctive tags that allowed them to study migration both within and between the two classrooms; the adjoined space in this case was literally the adjoining wall between the two classrooms.

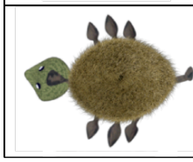
Morphology	Behavior	Habitat	Population
	Move along pipes Jittery motion Responds to noise moves slowly	Prefers cold; indifferent to humidity	Large
		Prefers heat; indifferent to humidity	Large
	Moves along pipes Linear motion, slow Responds to noise moves rapidly	Prefers humid; indifferent to temperature	Medium
	Moves along walls Wander motion Non-responsive to noise	Prefers dry; indifferent to temperature	Small

Figure 8: Characteristics of WallCology species used in 7th grade intervention.

Outcomes

Distributed collaboration. Collaboration surrounding the use of the adjoined spaces feature in the third grade unit was limited to the sharing of population counts of tagged creatures between classrooms, but nonetheless provided tentative evidence of the effectiveness of the feature in promoting authentic inquiry practices. Significantly different counts along the shared wall created an opportunity for class discussions of data anomalies, their potential sources (e.g., different counting regimens employed in the two classes), and the scientific need for repeated measures [5]. The use of adjoined spaces also appeared to have the effect of raising students' interest in migration patterns. While the migration of tagged creatures within each room was met with relatively limited interest, the appearance of "foreign" tags on creatures migrating from the adjacent room generated excitement and led to the articulation of new research questions concerning the speed and migratory ranges of the simulated creatures [6].

"Physical" science. At both grade levels, the nominally simple task of counting was problematized by the speed and density of creatures on the WallScopes, and evidenced an interaction between the ephemeral and responsive phenomena design features. As the students became aware of the complexity of the task they invented strategies for distributing the inquiry workload [6], typically with one student assuming the role of "recorder" while the other group members specialized in counting particular species.

[3] The decision to use imaginary creatures was the subject of considerable debate during our design deliberations; prior research had pointed to the inability of students to transfer abstract concepts to real-world phenomena [15]. We hesitated to use "authentic" creatures that inhabit walls (e.g., cockroaches and mice) because of the potential to frighten young children and also to avoid stereotyping the living conditions of the learners involved in the study. We were also pursuing learning goals that included dichotomous classification of animals and wished to avoid animals that could be found on the Internet. As a compromise, we designed quasi-realistic creatures with morphological features (e.g., fur, eye position, number of legs, etc.) that could be used as the basis for both classification and investigating habitat adaptation.

This teamwork started a bit chaotically but became more systematic as students found that loudly calling out the number of creatures did not work well since the loud noises tended to "scare" some of the creatures off the screen. The response to loud noises was especially challenging during the tagging activities, because the creatures would run too quickly for students to track and mark. As a result, the students had a tendency to be quieter during tagging in spite of their enthusiasm for the highly interactive task.

Interestingly, while the on-screen display afforded continuous access to environmental conditions, the requirement of retrieving, applying, and sharing portable instruments appeared to have a positive impact in drawing students' attention to local environmental conditions as the basis for explanations of habitat adaptations. This was evidenced most clearly in the third grade intervention, where the treatment differences allowed a direct comparison between the use of on-screen temperature and humidity displays in one class and the use of the portable simulated thermometers and hygrometers in the other class. In contrast to the other classes using WallCology, students in the third grade class using simulated instruments regularly referenced environmental conditions in their field guide pages, and out-gained (albeit not statistically significantly) their counterparts by 11% on a pre/post transfer item probing the relationship between physical characteristics and environmental conditions.

An unexpected reaction was the willingness of students to suspend their disbelief that WallCology was a simulation in spite of our explicit assertions to the contrary. In one instance, students were overheard asking construction workers in a nearby room, who were working on walls and ceilings, if they "had seen any little bugs running around on the pipes." Another student asked, "If they break the wall, would the bugs come out?" In support of their commitment to the reality of the phenomena, students even invented their own explanations as to why the creatures looked "a little cartoony," "because they are so small and that's what happens when you magnify them."

Granularity of observational loci. The introduction of mobile portals proved highly popular among the third grade students, with groups repositioning the portals, on average, 4.1 times per class period over the course of the unit. While the mobile portals raised interest in the activity, the variability in creature populations at different sites along a wall tended to complicate the task of determining creature counts and interfered with the instructional objective of tracking populations over time; in all likelihood, this was simply too much freedom to afford such young learners. However, the use of the mobile portals did result in several groups redefining the activity to include the "mapping" of the distribution of creature types along a wall. While population variability along a wall was an unintentional artifact of the probabilistic simulation unrelated to the instructional goal, the interaction affordance allowed students to invent new research questions and develop operational strategies for achieving those goals, an important component of authentic inquiry [6].

Learning. Among the seventh grade students, the attempt to orient students to issues beyond morphology in differentiating species proved only partially successful. While students were more strongly oriented toward physical characteristics in class discussions ("when I get to behavior I get kind of confused, I lose my confidence"), their field guides and interviews reflected fairly rich descriptions of behavior, including reactions to noise and speed of travel, albeit sometimes attributing relationships that were not programmed into the simulation ("The [slug] is scared of the turtle-like thing and that's' [why] we think it never comes out [of] the pipes"). Overall, though, students did not show improvement on pre-post items related to the use of behavior as a cue to species identification.

The more concrete goal of learning population estimation techniques proved reasonably successful. On an open-ended item administered before and after the unit, students were asked to describe two methods of estimating populations from samples. Reponses were coded on a 10-point scale, assigning credit for factors including the recognition of the inability to access or manipulate the full population, the need for multiple observations over space and/or time, description of qualitative algorithmic method, and articulation of quantitative formulae. Mean scores on the item increase from 4.6/10 (pre-test) to 7.6/10 (post-test), $t(21) = 6.15$, $p < .001$. Post-activity interviews with students, however, indicated that while students found the tag-recapture method to have intuitive appeal, and in several cases could describe and apply the Lincoln-Peterson formula, none were able to give a strong characterization of its conceptual motivation.

In the third grade unit transfer tests, students show pre-post gains in associating some morphological features with habitat characteristics (e.g., the association of body fur with colder habitats, pre-test M=.34, post-test M=.56, $\chi^2(1) = 4.6$, $p < .05$), but failed to show improvement on more subtle morphological characteristics. Student ability to properly sequence insect life cycle stages improved (pre-test M=.51, post-test M=.82, ($\chi^2(1) = 7.9$, $p < .01$), but no gain was seen on mammalian life cycles (likely due to a ceiling effect). While students nearly universally correctly identified the food chain in their field guides, there was no improvement in their ability to predict the impact of perturbations in predator or prey populations among hypothetical populations.

Stances toward science inquiry. Seventh grade students were administered affective items drawn from the TOSRA (Test of Science Related Attitudes) instrument [12] to assess attitudes toward science inquiry. On that test (scaled Strongly Disagree = -2 through Strongly Agree = +2), students' recognition of the need for multiple samples to increase reliability was evidenced through their responses to the item, "Repeating experiments to check my results is a waste of time" (pre-test M=-.32, post-test M=1.0, t(21) = 2.73, p < .05). Items relating to students' stances toward investigation also trended in the direction of increased agency, including "Doing experiments is not as good as finding out information from teachers" (pre-test M=-.23, post-test M=-.77, t(21) = 1.74, p = .10) and "I would rather do my own experiments instead of finding something out from a teacher" (pre-test M=.32, post-test M=.73, t(21) = 1.82, p = .08).

CONCLUSION

Rogers' broader agenda of a ubiquitous computing paradigm based on "proactive people" rather than "proactive computing" resonates strongly with contemporary views of learning as the active construction of knowledge. In the WallCology classroom, things are anything but calm, but neither are scientific investigations in real labs and fields, replete with local and remote interactions with colleagues, myriad tasks, negotiations, decisions, and on-the-spot development of strategies, all enabled and constrained by the perceptual, cognitive, and motor capabilities of their participants. When we deny learners the opportunity to engage in the full "messiness" of scientific inquiry, we run the risk of promoting the development of cognitive processes that are quite different from those used in authentic science investigations, and of fostering epistemologies that are may antithetical to the actual practice of science [6].

In this paper, we have argued that the way we choose to employ those technologies should focus not on making tasks easier for students, but rather more authentic, by problematizing the previously unproblematic. In our experience, students warm to the challenges of this kind of physical, engaged activity.

At the same time, it is always imperative to point out the importance of the instructional designs and scaffolds provided by classroom teachers. Embedded phenomena, including WallCology, are not in any sense self-contained "learning applications." Instead, the design of instruction and the design of technology proceed in parallel, mutually informed by curricular goals, classroom practice, and advances in technology.

An outgrowth of our focus on authentic science inquiry and development of the WallCology application has been the addition of generalized extensions to the "embedded phenomena" paradigm—including the concepts of adjoined spaces, responsive phenomena, the incorporation of mobile devices as simulated instruments, and perhaps most significantly, the uncoupling of observation sites from interaction media—while remaining faithful to the goal of employing technologies readily accessible to schools.

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