Embodying Scientific Concepts in the Physical Space of the Classroom

Peter Malcolm (pmalco2@uic.edu), **Tom Moher** (moher@uic.edu), **Darshan Bhatt** (dbhatt4@gmail.com),
Brian Uphoff (buphoff@gmail.com), **Brenda López-Silva** (brenda@cs.uic.edu)
Department of Computer Science
Electronic Visualization Laboratory
University of Illinois at Chicago
Chicago, IL 60607-7053 USA

ABSTRACT
Several simulation environments exist that create a place in which students can explore scientific phenomena. In this paper, we propose design guidelines for creating a classroom environment that puts scientific concepts directly into that physical space. We examine the results of two implementations of WallCology, which we characterize as an embedded phenomenon, in elementary and middle-school classrooms. Several instances of innovative student inquiry emerged as a result of the design features. Along with the results of learning, we look at the relationship between an embodied approach to design and the imaginative role of the student.

ACM Classification Keywords
H.5.3 [Information interfaces and presentations (e.g., HCI)] Group and Organization Interfaces. K3.1 [Computers and Education]

INTRODUCTION
Children studying science can benefit from seeing evident causes and relevant effects in several ways. The memorization of facts and rote learning are certainly necessary in the classroom, but classroom inquiry can be memorable and enjoyable for students and can often be more effective at teaching science practices than more didactic methods [2]. After all, many educators would argue that action gives rise to knowledge [17] and that learning science by witnessing or, better still, by participating in the exploration of phenomena develops students' intuition.

Paul Dourish [5] draws a distinction between *space* and *place* that is represented in the difference between *room* and *chat room*. The first is a simple physical space, but could be a *place* for communication. The second is not a space at all, but is purely a place because of its social nature, according to Dourish. Teachers work to transform the spaces of their classrooms into places of learning. This raises design questions: what can children do *in* a classroom to hone their scientific inquiry skills, and what can designers do *to* a classroom to facilitate that inquiry? This paper presents a set of design goals that can effectively impart the meaning in the space of the classroom that will make it a place for studying and exploring scientific phenomena.

We suggest three general design guidelines that can be followed to generate technological support systems for classroom science inquiry. While these are by no means requirements, they have been proven to be viable in the framework of Embedded Phenomena [14] and can be leveraged to support whole-class inquiry and discussion. These are (1) a physical accommodation that accounts for the architecture of the classroom, (2) an interface that responds in a way that will pique students' interest in the subject material at hand, and (3) measurement tools or simulations of such tools that inform classroom investigation.

The first design guideline determines the spirit of the interface. Unlike Virtual Reality (VR) or fully immersive environments, where the technology sometimes dominates the room, Embedded Phenomena take the opposite approach. The displays and other affordances span the classroom, and the technology is set up to correlate the simulation with the pre-existing physical space. In this way, the room itself is pivotal to the technology. The classroom-wide nature of the simulations also allows children to explore them together in Computer Supported Collaborative Learning (CSCL). Since some elements of the investigation are suggested by the technology, students' imaginations can further augment the shared reality.

The second and third general design guidelines correspond to the notion of investigating causality. Children using the technology in the classroom can test the limits of the simulation in embodied [5] and sometimes surprising ways, and can take measurements with the accompanying tools to quantify their results.

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Since we are concerned with technology that supports the study of science, each of these guidelines can be followed according to logic that concerns a specific scientific discipline. Here we will examine an example of an embedded phenomenon, WallCology, which helps to teach life science to primary- and middle-school children.

THE EMBEDDED PHENOMENON MODEL

Embedded Phenomena are a class of persistent simulations of scientific phenomena that are distributed throughout a classroom to provide students with opportunities to perform investigations. In previous installations, the simulations have used Tablet PC computers that can be affixed to the walls of a classroom to allow students a view of unfolding events. Such investigations are extended over a period of weeks, so that the students involved can collect large amounts of data to test and form hypotheses in a way that approximates professional empirical investigations [14]. In the past, students have used embedded phenomena to investigate plate tectonics and earthquakes (RoomQuake), infestations of insects (RoomBugs) and the orbits of the planets in the Solar System (HelioRoom).

Previous installations of Embedded Phenomena have demonstrated that 'convincing simulations can be created with minimal technical affordances' [19]. The unit under discussion here extended the model to include larger screens and portable displays, which we will examine in more detail below. WallCology also extends the Embedded Phenomenon model to allow students to explore the physical space of the simulation in new ways.

WALLCOLOGY

WallCology is a virtual ecosystem that purportedly exists within the walls of a classroom. The simulation includes members of a handful of vertebrate and invertebrate species that crawl across walls and along pipes that are visible through 'Wall-Scopes,' i.e. the computer screens. These represent two habitats for the simulated creatures. Large creatures inhabit the inner surfaces of the walls while smaller creatures live on pipes. Each 'WallScope' reveals a different segment of plumbing or gas lines with brick or drywall background visible behind it.

In the implementations described here, the primary learning objective was to familiarize the children with research techniques and methods that biologists use to study animals in the field. Students studying WallCology collect and share morphological data ('what the animals look like') and behavioral data ('what the animals do'). The researchers collaborated with classroom teachers in K - 8 grades to develop supporting materials with which to study the phenomenon. Field Guides, in the form of folders containing data-collection sheets, allow the students to record their discoveries. Large wall-charts allowed students to track global population trends of the various creatures in the simulation.

SOFTWARE MODEL

Embedded Phenomena simulations are based on a client-server model, wherein the server, implemented using MySQL and Java, maintains all global information about individual elements. In the case of WallCology, this meant locations of creatures within a global grid. The client application is written in Flash Actionscript and it generates the fine details such as a creature's exact location and appearance within a specific node of the grid. This model allows for remote management and administration of the phenomena, which in our case made use of the Internet and widely available web-based technology.

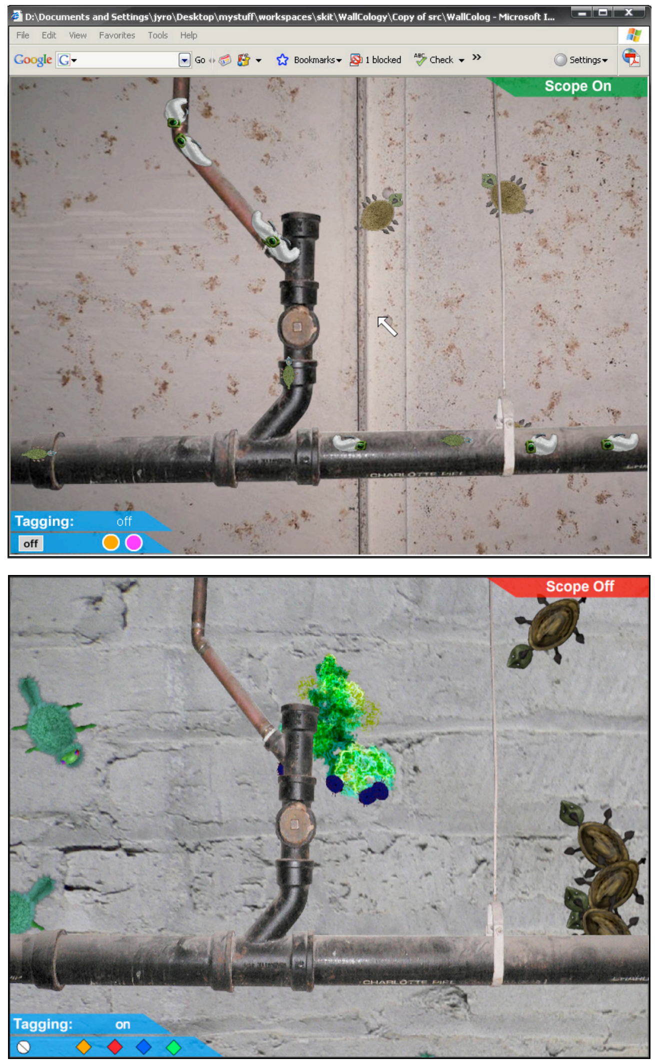

Figure 1: Two versions of WallCology, with creatures on pipes and the wall

RELATED WORK

Embedded Phenomena use the concept of augmented reality and are related in nature to Participatory Simulations [3] Participatory simulations give children the roles [11] of agents in the simulation so that they may ‘participate’ in emergent behavior, while many simulation tools such as StarLogo [18] let multiple instances of simple agents generate emergent behaviors on their own. WallCology allows students to interact with individual agents in a simulation, so that students are familiar with the behavior of the individuals, and global trends emerge from traits that students can witness in those individuals.

This demonstrates the second design feature, above, of a phenomenon that draws the attention and interest of students by interaction with its component parts. However, the whole-classroom nature of the simulation creates an experience for students that is comparable to such pervasive technologies as The Hunting of the Snark and Ambient Wood [10]. These technologies were built on the idea that children respond positively to an expanded physical space of exploration, and that increased space will generate self-directed forms of interaction.

METHODOLOGY

The simulation has undergone two classroom iterations, both in large urban kindergarten through 8th-grade public schools. For the first implementation, the researchers brought WallCology into a seventh-grade classroom (12 and 13-year olds) and for the second, they divided it across two adjoined fourth-grade classroom (9 and 10-year olds). Each implementation lasted approximately four weeks, and the children engaged in the study of WallCology multiple times per week during hour-long lesson periods.

Children are divided into teams, each of which is tasked with studying a different region of the room. They use the Field Guides to record the morphological data and note specific examples of their behavior. The seventh-grade students also sketched pictures of the creatures to familiarize themselves with the simulation's creatures. Along with pictures and written descriptions, the Field Guides allowed children to track quantities of creatures, so that teams of student researchers could share their population data at the end of each class period.

The means of assessment consisted of interviews and written tests, administered before and after the unit. Audio log files from the computers also provided a record of sound levels in the classroom, and the researchers recorded video footage of what happened in class each day. In addition to these records, the researchers used the children's Field Guides to provide a documentation of their work.

STUDENTS' OVERARCHING MOTIVATION FOR INVESTIGATION

Children use WallCology to investigate several species of creatures that have been 'discovered' within their walls. The researchers' treatment of the question of the simulation's genuineness differed between the seventh-grade and the fourth-grade installations. During the WallCology unit in the seventh-grade classroom, the researchers and the participating teacher left the question of realness ambiguous, so that students would decide individually whether they thought actual creatures inhabited their walls or not. In the fourth-grade classroom students were told explicitly on the first day that what they were seeing was artificial, but that they were to research it 'as if it were real'. In both cases, students were put in the role of research scientists so that they could form questions, follow lines of inquiry and discuss results.

The duration of the WallCology units were divided roughly in half according to the activities and the topical focus. During the first half, or two weeks, the students collected qualitative information about the creatures in the simulation, directing their attention to the animals' physical characteristics and their local behavior. The second half of the unit required that students collect population samples and thus generate theories about the creatures' global behaviors and population trends.

Instructional goals for the students included developing a simple classification scheme for the creatures and identifying which of their features might be seen as adaptations to the environment. For example, the salient feature of certain slug-like creatures that preferred cold temperatures was a white fur coat, while the creatures that preferred warmth had a scaly skin. During the second half of the unit, the study of populations motivates such questions as, what the creatures do while they are not visible, how many creatures exist that cannot be seen, and what causes the creatures to enter or leave the visible spaces. The fourth-grade installation of WallCology also used a dynamic population model, so that creatures could eat other creatures and produce offspring. Thus it facilitated the teaching of predator-prey relationships and food webs.

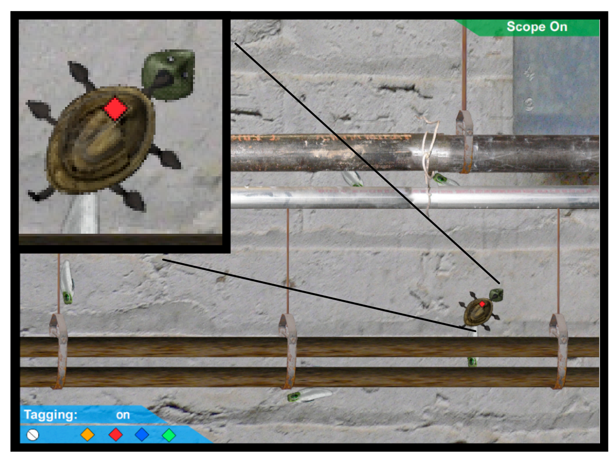

Figure 2: Screen snapshot with detail of a turtle that has been tagged

EMBODIED DESIGN ELEMENTS OF WALLCOLOGY

WallCology uses a responsive interface, so that creatures in the simulation respond to sound coming from the computers' built-in microphones. A specimen of one species will proceed slowly when frightened by high noise levels, while members of a different species will move quickly. The students were encouraged to take note of the creatures' reactions to noise. Students were very aware of this during the seventh grade unit, and less so in the fourth grade classrooms where the students made sufficient noise to maintain the creatures in this 'frightened' state perpetually. However, the seventh graders learned to investigate the simulation quietly to avoid scaring the creatures away.

Students could also 'tag' the creatures by touching them with styluses. A tag would appear as a colored dot on a creature's back as if the student had painted it there, and it would remain on the creature for the duration of the simulation (Figure 2). This task for the students physically approximates actual interaction with the characters in the simulation more faithfully than the usual point-and-click interfaces to which they are accustomed. Entomologists studying real insects need to catch those insects in some way. Field biologists frequently need to handle the animals they study, and WallCology includes something analogous by way of tagging. The tags also served as aides in measuring populations and migration trends as they would in the field.

In one of the fourth-grade classrooms, the designers also made use of iButton technology to allow multiple viewing locations for the phenomenon. Portable displays could be moved, and had USB attachments that could be plugged in to various 'buttons' on the walls, each corresponding to a different section or node of the grid. This required groups of investigators to negotiate which node or button to use, and highlighted the distribution of the underlying population that the students were studying.

In order to help focus students' attention on environmental factors, they were given portable devices that indicated 'temperature' and 'humidity' information. The researchers provided the students with small video iPod Touches with a web-based thermometer/hygrometer application that provided the environmental information from the application.

RESULTS: FACTUAL LEARNING

As a teaching tool for imparting propositional knowledge about animal habitats and adaptation, life cycles, predator-prey relationships, and population dynamics, WallCology proved moderately successful. The 41 students in the fourth-grade classes demonstrated an enhanced understanding (pre-test M=.34, post-test M=.56, $\chi^2(1) = 4.6$, $p < .05$) of the correlation between creatures' physical characteristics and their preferences for certain habitats. The same students also improved significantly in their ability to order the life stages of insects (pre-test M=.51, post-test M=.82, ($\chi^2(1) = 7.9$, $p < .01$). These younger students did not demonstrate significant gains in their approach to population estimation over distributed area. However, the seventh grade students did improve noticeably (4.6/10 (pre-test) to 7.6/10 (post-test), $t(21) = 6.15$, $p < .001$) on a question that was coded on a 10-point scale. The question dealt with how well the students understood the nuances of estimating distributed populations by repeated counting and averaging.

Figure 3: Students investigate WallCology and tally their results

MEANING MAKING: THE INVESTIGATIVE PROCESS

Scientists must engage in investigation of meaning both before and after performing studies. The traditional 'scientific process' involves creating hypotheses, testing those hypotheses, and then synthesizing the results. The testing of hypotheses thus gets sandwiched between the process of forming hypotheses and the ultimate synthesis of the resulting data in the classroom.

The richness of an investigative space such as WallCology provides for discussion that educates a student in two ways. First, initial student curiosity during class discussions can inform the investigation, usually during the process of forming their early hypotheses. Second, the investigation itself provides not only answers to the hypotheses, which satisfies the traditional heuristic 'scientific method' but also provides space new questions. Students, with the guidance of the teacher [4] are left with the need to discover not the right answer, but rather *the best available answer*.

Our analysis of the students' emergent investigations will be informed by first looking at the questions that the students asked at the very beginning of the WallCology units. In the fourth-grade unit, students were encouraged to form their own driving questions during the initial briefing. The theme and the technological affordances ignited curiosity in the students from before they began to study the simulation. Two questions that many students had were "Where did the animals come from?" and "What do they eat?" Thus the topics of animal migration and food webs, which dominate much of what is available to students in an investigation of WallCology, both emerged organically from the curiosity of the students themselves.

STUDENT INVESTIGATION: QUIETNESS, TAPPING, LISTENING

The seventh-grade students learned to remain relatively quiet while they investigated WallCology. It was a method of inquiry that the students developed independently of the teacher's instructions. Because the creatures' tendency to get frightened and run away, the simulation required this moderate silence for successful study, which the students discovered through their interaction with the interface. In an urban setting, people have limited interaction with animals apart from pets, pigeons, or what they may witness in zoos, and few city dwellers are likely to interact with creatures sensitive to sound. It is widely believed that action constitutes learning [17] and urban students engaging, quietly, with creatures, even simulated ones demonstrate an internalized cognizance for the creatures' sensitivity to sound.

Even more interesting are the methods that the children developed independently while they interacted with the technology. These included knocking on the wall, and on a separate occasion, putting an ear to the wall. The tapping incident occurred in the seventh-grade classroom shortly after a hardware malfunction required that the simulation interface be transferred from one of the wall-mounted tablet personal computers to one of the desktop computers that resided in the classroom. The boy tapped on the wall near the place where the original tablet computer had been, and closely watched the screen on the desktop computer to monitor the creatures' reaction to the noise. By this point in the class investigations, the students had conclusively agreed that the creatures were sensitive to sound and had adjusted their behavior accordingly. Thus tapping on the wall was a natural extension of the students' line of inquiry into the creatures' reactions to noise.

Shortly after their initial briefing, a girl in the fourth-grade class put her ear to the wall. A classmate in her group quickly tried to rebuke her by pointing out that the simulation was 'fake.' Nevertheless, she defended herself by replying that it was possible to hear sounds in the wall. The girl abandoned the technique after her first attempt, no doubt concluding that it would be too difficult to differentiate sounds audible in a classroom wall. However, her actions aligned directly with the investigative role that had been assigned to her in the class introduction to the simulation.

Both of these investigative techniques, tapping on and listening to the wall, require a robust investigative space. Children in the fourth-grade classroom claimed to have studied science by building baking soda volcanoes and also by bringing a rabbit into the classroom and doing a study to see how far the rabbit could hop. These are traditional classroom science experiments, but they are limited by certain constraints: materials the case of the volcano, and time and materials in the case of the rabbit. Studies involving volcanoes that use anything other than baking soda and vinegar, or perhaps water, demand that a teacher make very specific preparations. Factors that might influence a rabbit's jumping ability, such as, say, diet, also require time and careful monitoring to control, and the risk of frightening the rabbit by creating noise, as students did in WallCology, raise ethical concerns. Embedded phenomena and similar frameworks provide the opportunity for children to engage in spontaneous, harmless and sustained investigation.

STUDENT-GENERATED PROBLEMS AND SOLUTIONS

On a different occasion, the random, stochastic distribution of the creatures led the students to a different but equally innovative line of investigation. One group of children turned the hunt for creatures into a mock news program. While the camera was on a tripod, they enacted an extended scene in which they 'reported' on what was going on in the walls, what they were doing, and kept the 'viewer' updated. What follows is a transcription of the dialog:

[*J* stands in front of the camera holding a pencil as if it were a microphone*]
J*: Hi. My name is J*, and it is 18 squirrels, 1 pupa, 2 beetles and one egg. Now, we need to find even more bugs. We need to get turtles. There was no turtles.
S*: Now, we're about to count how many bugs, how many animals, how many pupas there is and insects. Now, [*to the camera, which is on a tripod*] you should count with us. Come here.
J*: Now, we're starting to count [*plugs the tablet computer into a button.*] Two beetles.
[S* plugs the Tablet PC into a different iButton]
S*: Now, there are two bugs now. Now it is 1:20 [the time] Two bugs now.
M*: How many skunks?
S*: There are three skunks and ... one turtle! two turtles!! Two turtles, two turtles!
J*: Two turtles
S*: Three!
J*: Three what?
S*: Three turtles

While the researchers had set up a structure for students to report on the number of creatures they witnessed in the simulation, they could not have anticipated this 'news-anchor' format. The Field Guides in which the students were to report their findings included sheets of paper on which to tally the quantity of creatures that appeared during designated population-counting sessions. These numbers were in turn transferred to large charts on the walls so that the children could witness global population trends. Meanwhile the cameras that were focused on the children were simply data-gathering devices for the benefit of the researchers, and we assumed that the children would largely ignore them.

However, the students clearly saw an opportunity to combine the significance of the tactical activity, counting creatures, with their natural inclination to role-play and report. The result was the impromptu news piece that served as a creative outlet and a scientific investigation simultaneously.

At the same time, the children generated a small, short-term investigative problem that fit neatly into the larger instructional question of watching population trends. When J* said 'We need to get turtles' he motivated further research for his group. The corresponding excitement that S* felt when she did finally encounter the turtles in the simulation verifies the notion that children feel empowered when they overcome 'internalized,' ideally self-created 'obstacles' during classroom investigations [15]. The students created this area of inquiry in response to the larger goal that the teacher and researchers put forth to quantify the creatures, presumably following a desire to see every possible type of creature during their research time in a way comparable to birdwatchers' attempts to see a large variety of birds rather than a large number of one particular species.

It is not surprising that this group did not witness a large number of turtles since their investigative site was one of the designated 'cold' sites that attracted few reptiles. In this interaction, the students did not attend to the temperature readings that were present in the simulation, and so did not reach these particular conclusions. However, this kind of discussion amongst the children lends itself well to the introduction of such causal relationships.

Other specific methodologies emerged in this pursuit of turtles. The fact that the children mentioned the time ("It's 1:20.") indicates an understanding of the need to provide metric data to support the rigor of their investigation. The children's high level of cooperation also stands out, from the changing roles of the individuals speaking: J* created the scenario, and S* elaborated on it, J* began the investigation, and then handed it over to S* to continue. When S* began to identify the intended target of study (turtles), M* and J* encouraged her to share her findings, which she did.

The teamwork that emerged during this interaction is reminiscent of forms of communities of practice [22] although on a small scale, with coordination and group problem solving techniques that emerged with J*'s initiation and S* following the lead.

ANALYSIS: TEMPERATURE AND CLASS DISCUSSIONS

The creators of WallCology designated temperature as an important independent variable for the children to study. Since they designed WallCology to be spatially embedded in the classrooms, the temperatures in the simulation were correlated to the architecture of the room. For example, walls shared with hallways and other rooms were 'warmer' than walls that faced the outside of the building.

This, in combination with the portable devices that the children used to measure temperature, appeared to have a formative impact on the dialog in the classroom. One of the fourth-grade teachers guided discussions very carefully after the children had gathered data about the creatures' population density in the simulation. She probed the underlying meaning of the creatures' distributions. Even random fluctuations in the density data often allowed for discussions that were relevant to the study of the creatures' behavior. In one conversation, a surprising dip in the skunk population in the classroom led one boy to conclude that the skunks were 'sleeping' or 'hiding'. After a girl in his class pointed out that it was 'colder now' (presumably referring to the outside temperature) the boy modified his hypothesis to posit that the creatures were 'hibernating'.

STUDENTS AFFECTIVE STANCE

Students in the seventh-grade class were given a reduced 28-question TOSRA (Test of Science-Related Attitudes) [9]. Their mean answers to two questions shifted enough to suggest a slight increase in the children's self-identification as scientists. "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, $t(21) = 1.82$, $p = .08$).

IMPLICATIONS

The impact that WallCology had on the learners that participated in it had some measurable effects. The fourth graders increased their knowledge of animals' habitats and their life cycles. The seventh graders gained knowledge of population sampling, and edged incrementally toward an increased view of themselves as independent investigators. Here we have also presented anecdotes that provide insight into the processes that children developed independently. Currently, the researchers involved are developing a study that will compare the effects of science investigation using the current versions of WallCology and RoomQuake [14] and their classroom-bound representations of real-time events with a control group of students exploring static records of the same events. This will allow for a rigorous comparison of learning modes.

We have seen various results of the design of the embedded phenomenon framework. The three design guidelines that we present, namely (1) accommodation to the space of the classroom, (2) a responsive interface and (3) real or simulated measurement tools, each have an impact on the ways in which children took on the investigation of the simulation. Each one of these draws on the imagination of the students. The first guideline is primary, perhaps, in generating the *place* of the investigation, and the other two follow naturally as extensions to it.

First, the whole-classroom physicality of the simulation led the students to spontaneously investigate of the walls of the room by tapping and listening. This type of embodied interaction [5] even beyond the periphery of the technology affordances implies an immersive quality that extends even beyond the technology. Papert claims that children's investigations of the world often approximate 'real science' more closely than 'classrooom science' does, and occur spontaneously [16]. The whole-class, augmented reality of the WallCology unit allows students to augment their repertoire of inquiry methods so that they can test the framework in various ways and find for themselves which ones are valid. This also implies that the framework effectively helped create the *place* of inquiry in the walls of the classroom.

The second two design features—the responsive interface and the measurement tools—underscored biological features of the creature preferences in the simulation. However, they could broadly be used, and spatial measurement has been in the past [14] to enrich the user experience. Augmented reality depends partially on users' imaginations, and the 'props' such as measurement tools or features such as responsive phenomena can heighten the experience by suggesting deeper meaning.

The contribution of the investigation in 'news program' format demonstrates the familiarity that students have with the needs of classroom inquiry. This could be attributed to first design feature as well, since the investigation used the physical space of the wall as its medium. At the same time, students shared their roles as scientists in the constructed community of practice [22] that their group formed. The collaborative nature of this investigation shows the traits of CSCL, as multiple learners benefited from the investigation simultaneously.

We conclude a study of design with the paradox that some of the most powerful results of a teaching framework will be those things that are not possible to predict. The problem is not intractable, but once it is recognized, it can inform design. In converting the space of a classroom to a place of investigation and inquiry, the latitude that children have to investigate is often as important as the subject material, the supporting technologies and the other scaffolding. Separating these elements becomes more and more difficult as technology becomes more flexible. Instead of attempting to tease them apart, we can unite them with the aim of aiding the imaginations of learners.

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