Participatory Simulations:

Building Collaborative Understanding through Immersive Dynamic Modeling

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ABSTRACT

The Participatory Simulations Project explores how a new kind of collaborative learning environment, which is supported by small, wearable computers, can facilitate collaborative theory-building and lead to a richer understanding of scientific experimentation. In a Participatory Simulation, participants become "agents" in a full-scale simulation. Unlike previous work, Participatory Simulations combines the notion of a microworld with the affordances of real world experience. By involving a large number of people (typically between 15 and 30) in a "life-sized" experience, the project brings a microworld off of the computer screen and into the physical world. In particular, this study explored the use of a series of Participatory Simulations in a high school Biology class. The students became "agents" in a simulation of a disease infecting their community. The results of this project show that Participatory Simulations fully engage participants in the simulation, facilitate collaborative problem solving, provide a substrate for collaboratively designing and running experiments, and support the definition of new vocabulary to discuss the underlying rules of the simulation.

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1.0 Introduction

The students in a science classroom are chattering away as they play with the latest computer simulation. A virus is about to wipe out a small community. Will the inhabitants discover a way to survive? A small group of students in one corner intently stare at a computer, waiting for the results. As they wait, the virus mysteriously infects a few players on the other side of the classroom. Shrieks echo through the room as each new set of red lights indicates that another player has succumbed to the disease. Each player struggles to evade the spreading disease. Without warning, red lights emblazon the whole population. The disease has run its course.

Think for a moment about the image that story conjures up for you. If you pictured this game unfolding, you might have pictured groups of students huddled around a desktop computer. Perhaps a few students sat close to the monitor while others jumped around behind them as their "players" fell ill. Perhaps a few fought for control of the mouse as they tried in vain to save their "player."

Much of our imagination about how computers can be used to enable new kinds of learning in the sciences is constrained by the box and monitor motif of the computer in the late 1990s. This thesis explores the notion of a Participatory Simulation, in which students are actually players in a unique, "life-sized" game that is supported by small, wearable computers. In keeping with the calls for inquiry-based science, developing skills for systems thinking, and fostering collaborative learning in science classes (Project 2061, 1993), this project explores how new kinds of learning can take place in the environment created by a Participatory Simulation.

Think back to the students watching the virus simulation. What did you picture? In all likelihood, you imagined a simulation running on a desktop computer, much like SimCity (1993)—a sort of 'SimVirus' or new virtual reality 'Outbreak' game. Children playing such a game would observe the results on screen and then decide how to use that information to better understand the model. However, the game described above is not played on a computer, at least not a traditional computer.

Participatory Simulations take the simulation off of the computer screen and bring it into the experiential world of the child. The students above are not just watching the simulation; in a very real sense they *are* the simulation. By wearing small computers called Thinking Tags, the students each become agents in the simulation. The students do not need to struggle to keep track of which player is sick, for the flashing red lights belong to their classmates. The questions that follow—Who got them sick? When? How? Why?—are not part of examining a computer model, they are part of discovering the underlying mysteries of their very own virus game.

This thesis addresses:

- The role experience can play in science learning,
- New ways to foster collaborative analysis and theory-building among a community of learners,
- The important role of experimental design in building scientific understanding, and
- The role computational objects can play as environmental mediators and conversational props.

In particular, it looks carefully at how Participatory Simulations create a valuable learning environment and explores the role that the Thinking Tag technology plays in that creation. Finally, this project provides some suggestions for studying these new kinds of interactive simulations as we continue to develop new ways for children to interact with the science in their worlds.

2.0 Background

There is a long history of theoretical claims that children construct their own knowledge through experience (Dewey, 1916; Papert, 1980). The experiences people have are often a direct result of some kind of interaction with their environment. These interactions, with other people or with objects in the environment, then serve as catalysts for development. For instance, as a child learns to catch a beach ball, she begins to construct a rudimentary understanding of motion in order to better predict where the ball is going and successfully move her hands to catch it. Repeated interactions with the beach ball will likely improve her ability to catch the ball and eventually may contribute to her building a better understanding of the movement of the ball.

Froebel pioneered the idea that particular objects, which he called "gifts", could be given to children in order to stimulate certain kinds of exploration. He argued that these gifts would provide experiences for children that would likely lead to certain kinds of cognitive development (Brosterman, 1997). [See also (Lillard, 1972) for related work.] For instance, his intent in providing young children with a set of multi-colored balls was not only that the students would play with the balls, but also that the presence of the balls would help them build more sophisticated kinds of thinking. Perhaps the children would begin to group other objects in the world based on color, beginning the process of learning to parse information by category; or perhaps playing with the balls would help solidify some of the earlier experiences of motion with the beach ball. Vygotsky wrote extensively on the notion that tools (like Froebel's gifts) could broaden and enrich the scope of activity and the scope of thinking of the child (Vygotsky, 1978). Fischer (1980) even speculated about the ways in which the objects present in the environment could actually induce development. [For another description of the importance of tools in the development of understanding see (Norman, 1993).]

As computers evolved, they were a natural candidate for the extension of these ideas. Papert envisioned a future in which computer-based tools would provide children with a whole range of transformative developmental experiences, much like gears (his own childhood tool) had for him (Papert, 1980). His notion was arguably the beginning of the attempt to use the domain of computer technology to build new tools for children. Since then, much effort has been expended to build computational tools that provide opportunities for children to engage in computer-based experiences, many of which would not be accessible to children without those tools (Resnick et al., 1998). Virtual communities offer places for children to construct alternative realities (Bruckman, 1997); microcomputer-based labs facilitate children's collection of scientific data (Tinker, 1996); and tiny Newtonian-based environments encourage exploration of the laws of physics (White, 1993). Some of these computational tools fall into a broad class of computational tools called microworlds.

2.1 A computational "sandbox"

In a real sandbox, children use buckets, shovels, and sand to create miniature castles. While creating these sandcastles, children often grapple with concepts like shape and scale. What base supports the tallest sandcastle? How big should the pebbles be if they are meant to represent a prince and a princess? Microworlds were originally conceived to give children a sort of computational sandbox—a small world in which students can manipulate "objects" on the computer screen. However, a microworld offers more than just a sandbox on a screen. In a microworld the actions you can take are determined by a set of formal rules that govern the interactions in that world. The computer becomes a bridge linking the patterns and activities in the world—images of shovels moving sand or balls bouncing through the 'air'—with the formal—usually expressed through symbolic representations of the underlying processes. This bridge enables children to interact first with the processes and patterns they observe and subsequently with the formal systems that govern those patterns and processes.

Much as Froebel intended his gifts to enhance children's activities in the service of helping them develop new understandings, microworlds can broaden the range of activities in which children can engage, especially by providing experiences that enable children to explore formal systems. Microworlds provide "a context within which children can think about discrete space as *real* and not about discrete space as *an* *abstraction* from the analogue worlds of sensory-motor experience" (Pufall, 1988). Many researchers have built upon these ideas, constructing various microworlds that facilitate many experiential possibilities (mediated by different formal systems). In fact, some even speculated that the new experiences provided by interactions with microworlds might "alter children's patterns of development, by allowing [them] to interact in ways [they] cannot interact with the "real" world" (Pufall, 1988).

Before examining the experiential environment of Participatory Simulations (Section 3.0) we will embark on a short journey through a range of microworlds in an attempt to delineate some of their salient features.

2.1.1 Microworlds by definition

A microworld, by definition, is a model of a slice of the world that operates by a partial set of formal rules. In other words, microworlds do not attempt to replicate all of the rules (and exceptions) that one finds in the real world. Instead, they operate on a chosen subset of rules, like Newtonian laws of physics or Turtle Geometry (Abelson & diSessa, 1980), that will govern cause and effect or action and reaction within that tiny world. In that world, there is no existential question about what assumptions govern behavior. With some exploration or investigation, all of the relevant underlying mechanisms can be unearthed. Different microworlds invite participation and exploration by users in different ways. Some microworlds greet users with a blank slate and users need to build up a project of their own design. Others provide a representation of some phenomenon and the users need to make sense of how the phenomenon works.

Let's look first at what we will call a "blank slate" microworld. These microworlds operate on a set of formal rules, enabling children to create their own patterns and processes in the world. A child might build a set of balls that can be moved according to Newtonian laws or create turtles that can draw specific geometric shapes. When a user enters this kind of program, she is greeted by a "blank slate." A large part of the child's task is defining what project she want to pursue (or what phenomenon she wants to represent). Then, in building the system or project that the child imagines, she needs to think through how to use the components (or primitives) of the microworld to construct her chosen project. For example, a girl might want to draw a square in the Turtle Geometry microworld. She might type:

fd 5
right 5
right 5
right 5

to make the turtle move forward 5 paces, turn right and move forward five paces, etc. However, in this case the turtle will draw a single straight line five paces long. This is because the pattern that the girl is imagining is not quite aligned with the pattern produced by the output of that symbolic representation in this microworld. While she *imagines* that right 5 will move the turtle five paces forward after a right hand turn from the last command, right 5 *actually* only turns the turtle five degrees to the right.

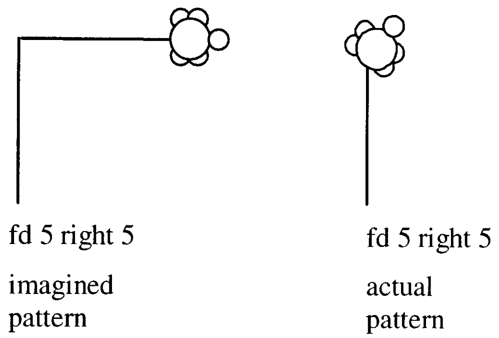

Figure 1: Imagined and actual patterns in a Logo microworld.

The way in which the child will figure out how to build a square is by struggling to align her desired pattern with the actual output of the formal system of the microworld, each time by comparing what she sees in her mind as the final goal of her project with what the turtle actually draws when it executes her instructions. This process might be one of trial and error or might be one involving extensive planning (Turkle & Papert, 1992), but regardless of the method, the child will manipulate the pattern or process by fiddling with the primitives she knows (or by learning new ones) until she produces a solution to her problem. In this case, the child will have solved her problem when she builds up the phenomenon she has imagined (a square) out of the underlying building blocks or primitives that the microworld provides.

Another use of microworlds is providing an environment for children to experiment with a phenomenon they see but don't yet fully understand. In the real world, a child might throw a ball up and catch it. He may do this repeatedly, perhaps hundreds of times. Each time he throws the ball it behaves in a predictable manner, which we know is because the motion of the ball is governed by an underlying set of rules. However, no matter how many times the child throws the ball, the environment only supports a limited investigation into *why* the ball behaves as it does.

Microworlds support a deeper exploration of why certain patterns or processes, like a ball bouncing, exist as they do. For example, a physics microworlds might present the following problem: A cannon fires a ball every time you press "enter." How can you make the ball land in a particular place on the screen? A child might start out by repeatedly firing the cannon, much like the boy who threw the ball in the air. Frequently, the ball may not end up on the right spot because the child's imagined result is not aligned with the how the underlying rules of the microworld operate on the ball (like the turtle drawing the square in the previous example). However, as the child experiments, the microworld supports his investigation into *why* the ball lands where it does.

Depending on the microworld, a variety of clues to the connection between the process and the underlying rules might be give. For instance, the microworld might provide visualizations of the forces acting on the ball or show equations describing the ball's motion. The child begins to experiment with the ball in the context of the underlying rules of the microworld. Ideally, experimentation with the cannon and the ball will soon begin to illuminate those underlying rules, and the child will be able to make connections between the pattern of motion and the underlying rules that govern the ball's motion. In this scenario, the child made sense of those rules by experimenting with a pre-fabricated phenomenon instead of building up his own project (e.g. Confrey & Doerr, 1994; Eylon, Ronen, & Ganiel, 1996; Roschelle & Teasley, 1995).

In each of these cases we have been talking about worlds in which children can explore ways to understand the underlying mechanisms of the microworld by aligning their understanding of the pattern or action of the system (or their experience of seeing the turtle move or the ball bounce) with the formal symbolic notation describing the underlying rules that govern the phenomenon (fd 5 right 90 fd 5 or $F = GMm / r^2$).

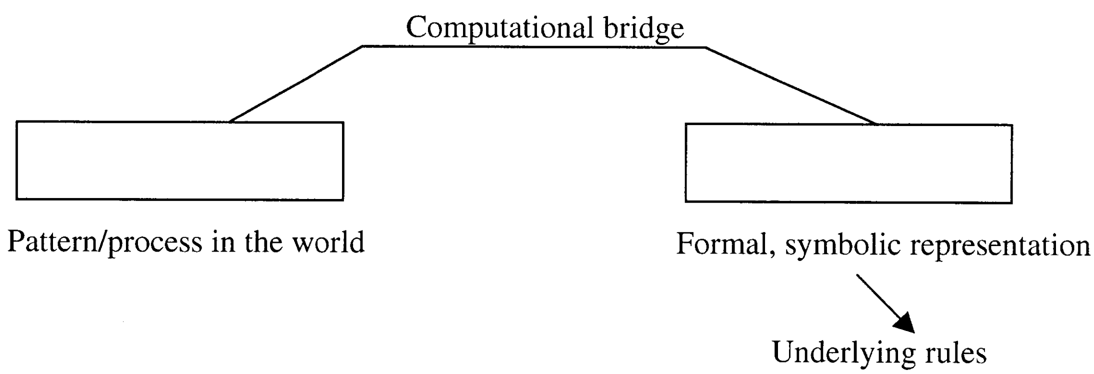

Figure 2: Computers can build a bridge between patterns and processes in the world and formal, symbolic descriptions of those patterns.

As children grow up they are prodded, frequently in school, to move beyond understanding phenomena in the world based simply on their experience and observation and move toward also understanding a formal representation of what they experience and observe. Unlike most childhood activities, such as throwing the ball, microworlds provide explicit links between the pattern or activity that is observed or experienced and a formal representation of the underlying rules.

Though historically the formal system to which patterns and experience are linked is mathematics, computers offer the opportunity to rethink the type of formal representation employed. DiSessa (1988) and others (Papert, 1980; Resnick, 1996b) have argued that we ought to use the power of computational environments to create formal symbolic representations that tie more closely to the activities, patterns, and experiences of children's worlds. In fact, diSessa maintains that the more we can make the formal representation mirror the experience or pattern, the better off the learners will be. He argues that microworlds that link these "semi-formalisms" to experience will be more useful educational technologies (diSessa, 1988).

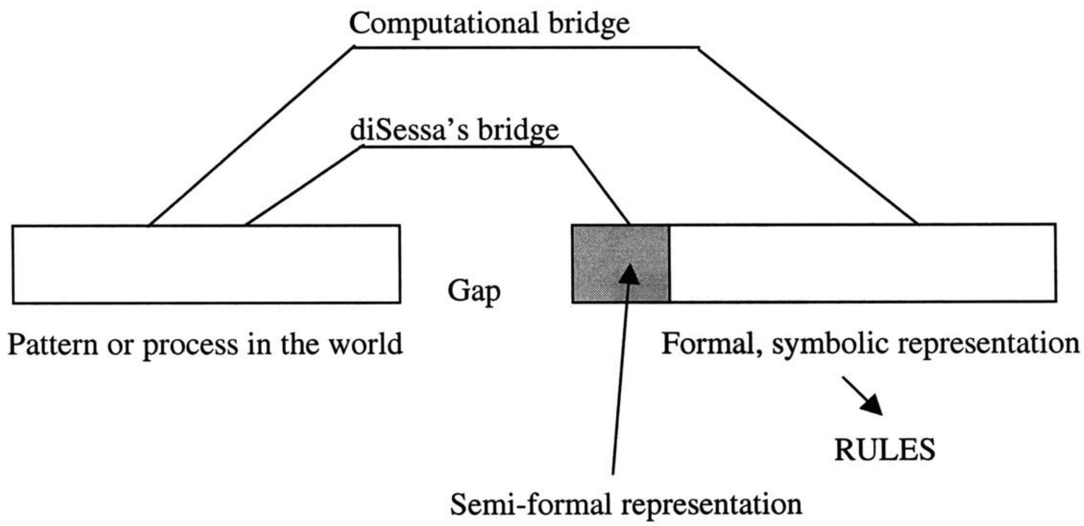

Figure 3: diSessa suggested that semi-formal representations that are more closely related to patterns and processes in the world could reduce the gap between those patterns and formal descriptions of the system.

2.1.2 Is there a way to learn more from experience?

Making a computational environment more like the world we observe is one way to try to build links between the two ways of understanding the world. [See (diSessa, 1988) for a discussion of the importance of bringing pictures of objects into an optics microworld.] As diSessa rightly points out, this practice sometimes becomes tricky to implement because the gap between formal systems and experience is often large; thus the attempt to narrow that gap through the use of semi-formalisms. Here, instead, we ask if there is another path linking the patterns and process we experience to their underlying rules?

Building microworlds in a computational environment provides an extremely deep, well-connected system of symbolic representations of coherent, consistent underlying rules. Here we will argue that moving off of the computer screen and into the experiential world has affordances of its own. By bringing computational tools into the real world, we can create an environment in which students' experiences are mediated by underlying rules that are consistent and comprehensible, facilitating a new kind of collaborative investigation into the relationship between patterns and processes in the world and their underlying rules.

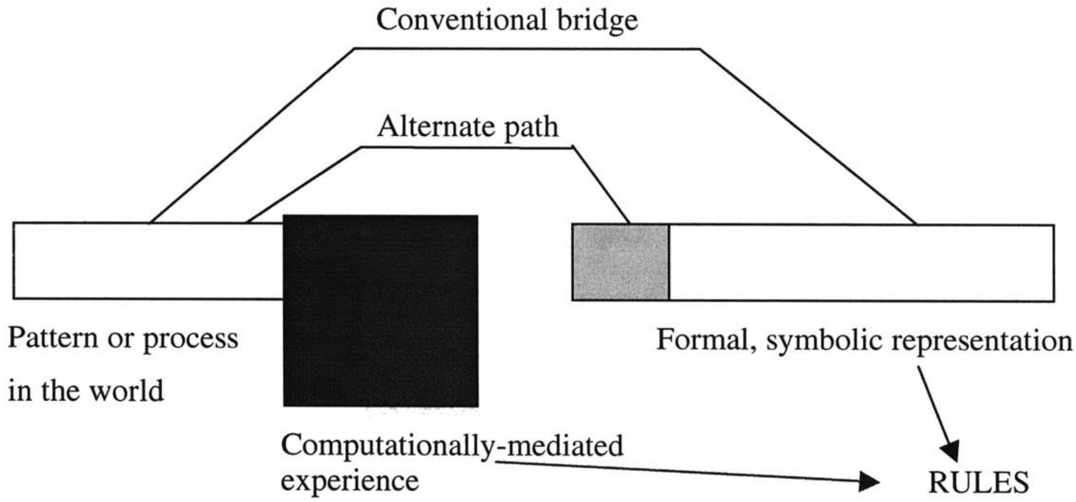

Figure 4: Participatory Simulations provide another path to access the underlying rules of a system by linking the pattern or process that is observable directly to the rules underlying the system.

The Participatory Simulations project is one example of creating such a computationally-mediated environment in "life-sized" space. We have taken a multi-agent simulation of a dynamic system and re-deployed it in a child's world.

2.1.3 A special kind of microworld

During the past ten years, simulation, especially as it helps people to understand complex systems, has become a mainstream use of computational technology. The widespread popularity of game software like SimCity (1993) and SimLife (1992) gives a clear indication of the extent to which simulation games have permeated popular culture. Programs like Model-It (Jackson, et al., 1994), Stella (Roberts et al., 1983), StarLogo (Resnick, 1994) and Sugarscape (Epstein & Axtell, 1996) enable users to experiment with complex systems and develop better intuitions about the mechanisms that govern dynamic interactions. The Participatory Simulations Project investigates how direct, personal participation in a simulation leads to a rich learning experience that enables students to explore underlying mechanisms.

The idea to use direct, personal participation to help children (or learners) gain a new perspective or build a new understanding is not a new one. In the social sciences, perspective-taking activities are quite common (Seidner, 1975). Students might be asked to take on the role of community activists or politicians and play-out (or simulate) a debate on the future of the logging industry. This simulated debate gives the participants a way to represent the characters and think about how the various characters might feel about an issue.

Activities like this are less common in the sciences, where the mechanisms to be studied are not human feelings and behavior but concepts like planetary motion or molecular interactions. Nonetheless, students sometimes take on those kinds of roles as well, perhaps pretending to be planets in orbit, in an effort to illustrate those phenomena. However, these activities are very different from their social science counterparts. While the social science activities might help the students to think about how a politician, for instance, would feel and behave under certain circumstances, the science activities don't necessarily help students to think about the underlying mechanisms of processes like planetary motion. Role-playing activities attempts to create links between personal experience and a deeper understanding of why that experience happened, yet the science-based activities often end up being little more than large-scale illustrations of a phenomenon.

Researchers have attempted to connect personal and physical interactions to underlying mechanisms in a variety of ways. Papert tried to forge links between human action and the rules of Turtle Geometry by asking children to pretend they were the turtle and then translate that understanding into a symbolic representation of the instructions for the turtle's movement (Papert, 1980). Resnick and Wilensky (1997) expanded upon this idea, involving large groups of people in activities to help them gain a richer understanding of the rules governing emergent systems. Participatory Simulations build on these large group activities, adding computational tools to create a bridge between experience and underlying mechanisms.

2.2 Collaborative learning

2.2.1 Importance of community

The development of computer-supported learning environments has coincided with a growing research interest in collaborative learning. Underlying much of the current research in ways to support collaborative learning is Vygotsky's assertion that knowledge is constructed within communities. He proposed a "zone of proximal development," a range of thoughts and activities that are just out of reach of an individual but can be accomplished with guidance from an adult or the assistance of peers (Vygotsky, 1978). [See (Polman & Pea, 1997) for an application of this theory.]

Recently, there has been an interest in looking beyond the learner as an individual member of a community and thinking instead about the learner as one component in a larger system. The model of a "community of learners is based on the premise that learning occurs as people participate in shared endeavors with others, with all playing active but asymmetrical roles" (Rogoff, 1994). The introduction by Lave (1991) of communities of practice argued for the definition of communities as coherent learning units. "Activities can be distributed among a group of students, such that distinctions that might be hard for an individual student to maintain can be encoded in the organization. The organization becomes an interpretive frame that provides the basis for a change in understanding" (Newman, Griffin, & Cole, 1989). The idea behind distributed cognition is that a community can be the unit of learning and that knowledge can be constructed by the group as a whole rather than just by individuals in a group. Communities themselves can participate in knowledge-building activities in which the whole community is involved in the construction and elaboration of knowledge.

Though the popular image in the domain of science is that of a single, brilliant scientist working long hours at his bench until he comes to some epiphany, in fact the practice of science is a good example of a distributed community working to amass information, solve problems, and plan future experiments. Roschelle talks about the importance of social construction of knowledge in scientific domains in terms of learning to practice science. "Learning to be a scientist is as much a matter of (1) forms of participation in social activity and (2) negotiation of shared meanings, as it is of (3) internalizing scientific representations and operations" (Roschelle, 1996). [See also (Driver, et al., 1994).]

2.2.2 Computer-supported collaborative learning

There is a growing emphasis on how computational tools might enable new kinds of learning in communities. "Computers and people working closely as partners in cognition have potential for fundamental qualitative changes to how we view human cognition" (Salomon, Perkins, & Globerson, 1991); quoted in (Reiber, 1995). The emerging field of Computer Supported Collaborative Learning (CSCL) is dedicated to examining how computational tools can facilitate collaborative learning (Edelson, et al., 1995; Goldman, 1996; Hewitt & Scardamalia, 1996; Koschmann, 1996; Lajoie, 1993; Resnick, 1996a; Roschelle, 1996; Tao & Gunstone, 1997; Teasley & Roschelle, 1993) and support the growth of knowledge-building communities (Riel, 1995; Scardamalia & Bereiter, 1991; Scardamalia & Bereiter, 1994).

As the CSCL community grows, much energy has gone into defining just what a piece of technology that supports collaborative learning ought to be. This has been (and will likely continue to be) a spirited debate (Derry & Lajoie, 1993; Hewitt & Scardamalia, 1996; Roschelle, 1995; Salomon, 1995). One proposed idea is that "a collaborative technology is a tool that enables individuals to jointly engage in active production of shared knowledge.... It allows the community to reconstruct a shared experience continually so as to produce greater meaning and greater potential for successful future action.... [the tools] function by becoming a highly visible part of shared experience" (Roschelle, 1995). Within the CSCL community there are two major types of tools that enable people to collaborate. One set of collaborative tools facilitates collecting data or evidence in service of solving a problem or building a case (Edelson et al., 1995; Scardamalia & Bereiter, 1990; Scardamalia, et al., 1989). The second set of tools enables collaborative problem solving through the exploration of a computational environment (Goldman, 1996; Roschelle, 1996; Roschelle & Teasley, 1995; Soloway et al.; Tao & Gunstone, 1997).

The first cluster of collaborative tools uses computer technology to foster communities of learners who can be separated by space or time but are linked by computational tools. Projects that employ these technologies typically involve many students contributing to a shared database or conversing over a network to share information and solve a common problem. These technologies and the associated activities account for a large portion of the work in CSCL. CSILE, the archetype of these technologies, enables students to collaborate by adding pieces of data or evidence relevant to a particular problem to a large database. For instance, students might work together on a project about acid rain, sharing their observations and questions through CSILE. As the students each contribute their observations and theories, this shared resource grows, and can be accessed and consulted as students discover new evidence or uncover new problems. Research has shown that students are able to collectively build up a knowledge base and can also build on each other's contributions of evidence, leading to what is known as collaborative theory-building. The tool, in this case CSILE, enables children to participate in a knowledge building-community (Scardamalia & Bereiter, 1991; Scardamalia & Bereiter, 1994).

These kinds of collaborative technologies link many students in a large community of learners. Each member of the community is working to explore a problem and has the benefit of the community's knowledge and understanding. In these learning environments, much of the information that is shared from one child to the next is shared via a technological link. In other words, the technology is the medium for the collaboration. The technology might be quite generic, as when email or listservs provide the means for information transfer from one child to another, or more specialized, as in the case of a shared database like CSILE that can help children organize and reflect upon their communication. In either case, the technology provides an additional connection between students and the means to create and access the shared database of information.

Of course, in any social learning environment, face-to-face conversation is a significant component of collaboration. In fact, some CSCL tools have been designed to capitalize on this natural mode of communication. The second cluster of CSCL tools fosters collaboration between students who are working together in real-time and real-space to solve a problem. These computational tools provide the setting for experimental design (Jackson et al., 1994), hypothesis testing, and problem solving (like the microworlds discussed above). The computer can provide representations, often visual, that help children settle on an interpretation of the problem. While using these tools, interactions among children take place primarily in a non-technologically mediated manner. In other words, spoken language and gestures convey much of the meaning transmitted from one child to the other (e.g. Roschelle, 1992; Roschelle & Teasley, 1995). Studies of these tools frequently focus on the interactions between a small group of children as they work together. This class of collaborative technologies provides a different kind of environment for student-to-student collaboration and circumvents one of the challenges of CSCL, namely, the barriers that traditional computers pose for face-to-face communication (Koschmann, et al., 1996).

The Participatory Simulations project employs technology in a social context to create a new class of collaborative learning environments. The activities of Participatory Simulations borrow features from both of the traditional CSCL tool domains and integrate them into a different kind of learning environment. Participatory Simulations retain the community knowledge-building aspects of programs like CSILE by creating a setting where all children can work together to gather evidence and form theories about the simulation. In addition, since the students are all working on a common simulation problem in real-time and real-space, they can engage in productive face-to-face collaboration. Furthermore, because the Tags create a computational environment based on consistent and comprehensible underlying rules, students can collaborate on designing and running experiments to elucidate the dynamics of the system.

By drawing upon these features, Participatory Simulations builds on previous research in CSCL, while simultaneously creating a new learning experience. Moving the simulation off of the desktop computer and into the student's experiential world gives participants in these simulations a new way to understand dynamic systems through personal experience.

3.0 A new environment for collaborative learning

The Participatory Simulations project proposes and evaluates a new collaborative microworld. The following four features situate this new learning environment in the context of prior work.

1) Immerses students in a constrained problem.

Like some microworlds discussed above, Participatory Simulations create a microworld in which the problem has been posed for the students. The challenge is to manipulate the agents of this microworld to uncover the underlying mechanisms that govern its behavior, not to create a new problem from scratch. However, in this problem, the students *are* the agents and the problem is *their* experience.

2) Creates a unique link between experience and underlying mechanisms.

Researchers in microworlds have claimed that the computer can serve as a bridge between pattern or experience and formal representations, but have realized that this is often too large an intellectual leap for some students. Participatory Simulations builds this bridge in a new way, creating an environment that provides computational support both for an immersive activity and for the participants' subsequent attempt to make sense of that activity.

3) Builds on the affordances of previous work in CSCL.

Students are able to collaboratively collect and analyze data about the simulation. They are also able to design and implement experiments to test hypotheses. Participatory Simulations leverage off of the affordances of face-to-face communication and collaboration while providing an opportunity for facilitating knowledge-building communities.

4) Provides a setting in which students can begin to construct a vocabulary to describe the underlying rules.

Participatory Simulations do not link activity to a prescribed formal, symbolic system. Rather, by providing an experience that is computationally-supported, they create an opportunity to explore the activity and in so doing empower the participants to devise their own vocabulary to describe the underlying rules.

3.1 The Participatory Simulations Project

The Participatory Simulations Project looks specifically at how a new kind of collaborative learning environment, which is supported by small, wearable computers, can facilitate collaborative theory-building and lead to a richer understanding of scientific experimentation. The Participatory Simulations project enables direct, personal participation in a simulation environment. This environment, like its microworld cousins, is a computationally-supported world governed by a specific set of rules. Unlike previous work, Participatory Simulations combines the notion of a "formal sandbox", or microworld in which models can be run, with the affordances of real world experience. By involving a large number of students (typically between 15 and 30) in a physical, "life-sized" experience, the project brings a microworld off of the computer screen and into a child's world. The next section will briefly introduce the activities of Participation Simulations and the way in which those activities are technologically and pedagogically supported.

The Participatory Simulations Project focuses on the whole group's interactions, as mediated by distributed, wearable computers. These group interactions occur both during the simulation, as players interact, and perhaps more significantly after the simulation, as players work together to build an understanding of the mechanisms of the simulated model. The emphasis on whole-group interactions stems from the hypothesis that dynamic systems might be better understood if models of those systems could be experienced and analyzed collaboratively.

4.0 Study

4.1 Methods

The Participatory Simulations project consists of one extended study in a local, public high school. That three-week engagement was informed by a number of pilot studies, including a week-long set of activities at a local public elementary school, a teacher-training workshop, and several pilot studies in summer, 1997. Additionally, a set of four Participatory Simulations was observed at a rural public school in Ohio. In sum, close to 800 people have now participated in different versions of Participatory Simulations at different points in the design and development process. Certainly, observations and data collected during these activities have helped shape the analysis presented here. However, the study at the local high school is the focus of this thesis and provides the core of evidence for the conclusions reached in this project, as outlined below.

4.1.1 Participants

The Participatory Simulations project was conducted in a public high school classroom in Cambridge, Massachusetts. All of the students volunteered for the project and were told that they would be participating in a project to learn about dynamic systems in science. Class time for five days over a three-week period was entirely devoted to activities associated with the Participatory Simulations project. The chosen Biology class consisted mainly of tenth grade students, most of whom were of low ability levels.[1]

Sixteen students participated in the study, though two students were only present on the first and second days and one student was absent on the last day. (Bringing the subject totals to 16, 16, 14, 14, and 13 for the five days of the study.) The teacher also participated in the activities, though he did not teach any of the classes, and on day four a student teacher observed the class and participated in the activities. In addition, two

[1]Because this study was intended to identify features of Participatory Simulations that support whole-group collaboration, not the acquisition of specific content knowledge, no differentiation was made among the participants and specific information about their previous academic achievements was not collected. However, it is fair to remark that the participants generally had very low skills in Science, were reading well below their grade-level, and in at least three cases had previously dropped or failed out of Biology class.

students videotaped the activities. One student was a member of the Biology class who preferred to not be filmed for religious reasons, and the other was a classmate from a different Biology class.[2]

4.1.2 Technological Support

To enable direct participation in the simulation, this project takes computer simulations off the computer screen and brings them into the physical environment. Previous work has explored bringing computation to objects and people in the real world (Ishii & Ullmer, 1997), augmenting a person's interactions with the world (Feiner, et al., 1997; Feiner, et al., 1993; Starner et al., 1997), and providing users with real-time, contextual information (Rhodes & Starner, 1996). This project borrows some ideas from personal or wearable computing by outfitting each participant with their own Thinking Tag. Participants wear the Thinking Tag throughout the simulation. Like wearable computers, the Tags collect information for the participants and help them to interpret the state of other players (for example, whether someone is "sick" or "healthy").

Unlike the traditional notion of wearable computing, however, the Tags connect all of the participants in a common, discrete network, which provides the computational support for the simulation. Rather than just transforming the experience of an individual, Participatory Simulations transform the interactions among people by linking them through a personalized network of communicating computers. Each participant becomes a player in a digital system comprised of people and their small, personal computers.

Participatory Simulations are supported by a variation of the Thinking Tag technology developed at the Media Lab (Borovoy, et al., 1996). The Tags are used to transform each participant into an "agent" in a life-sized simulation of a dynamic system. In order to create an environment that fostered this kind of "first-person" simulation, which could be collaboratively analyzed, we developed a new version of the Thinking Tags specifically

[2]Most of the students in the Biology class were not accustomed to being videotaped, and it was hoped that avoiding the circumstance of many adults descending on their classroom would keep distractions to a minimum. This seemed to be a largely successful strategy.

for use in this project.[3] Like the original Thinking Tags, the Tags built for Participatory Simulations have both an infrared transmitter and receiver, allowing them to dynamically exchange information with all other badges in the simulation. (In these decentralized systems no one badge acts as a server.)

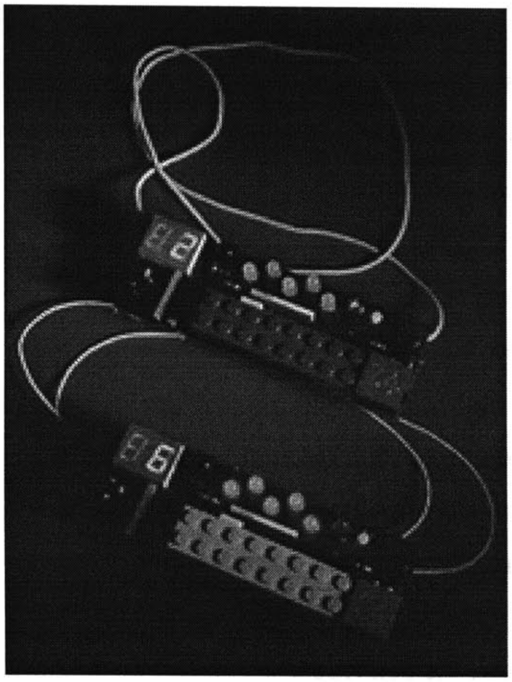

Figure 5: Two virus Tags. The top Tag has met two people and is not sick. The bottom Tag has met six people and is sick, as indicated bv the five red LEDs.

The Tags have two output devices, a double digit number pad and five bicolor LEDs. During the simulation the information displayed on the Tags changes, and participants watch the Tags to discover information about themselves and about other players. A resistive sensor port acts as another input, allowing users to attach small tools to their Tags, enabling them to "dial-in" information or change the program their Tag is running. This carefully chosen set of inputs and outputs provides a rich set of user interactions, both during the simulation and during the subsequent analysis. As in the original Thinking Tag design, we took care to ensure that the enhanced information display would not interfere with participants' social interactions (Borovoy, et al., 1998; Borovoy et al., 1996; Ishii, Kobayashi, & Arita, 1994).

4.1.3 Activities

In the Participatory Simulations project, students participated for 45 to 55 minutes on each of four days and 90 minutes on the last day (except for the last day, they participated during their normal Biology class period, which varied slightly in length each day.) The project was divided into three distinct phases. On the first day (phase 1) students were introduced to the researcher and a few other examples of technology that operate on the same general principles as the Tags (Resnick et al., 1998). On days two,

[3]Special thanks to Kwin Kramer for designing and building this version of the Thinking Tags.

three, and four (phase 2) students participated in disease simulations and analyses of those simulations. This phase had three distinct components: the initial disease simulation, the discussion of that simulation, and the development of experiments to test hypotheses about that simulation. The students completed six disease simulations over the course of the three days, with the discoveries from one simulation leading to the design of the next. Finally, on day five (phase 3) students reflected on their experiences in the Participatory Simulations project and participated in one final simulation.

4.1.4 Data collection

The Participatory Simulations project uses a qualitative model of research. Data was gathered to gain a rich sense of participants' interactions through a close analysis of the whole group of students. The goal of this thesis was to gather evidence for the importance of "first-person" participation, or immersion, in a large scale simulation and the occurrence of collaborative theory-building and experimental design. Bringing new computational tools into a classroom can fundamentally alter the structure of the class's interactions. Thus it was particularly important to address the activities and conversations of the group as they proceeded through the activities.

Research into collaborative activities can focus on conversation both during and after the activity. The conversation during the activity deals primarily with the actual problem at hand—what we might call process-centered conversation. The latter conversations consist mainly of reflections about the activity. While both kinds of conversational data were collected in this project, the choice was made to focus on conversations and explicit collaborative discussions during the activities. The process-centered conversations provided the most complete information about how the collaboration among students was proceeding and evolving. Also, many of the student volunteers had relatively little experience 'thinking out loud,' so the choice was made to avoid pre- and post-interview questioning.

The unit of analysis in this study was not the individual child nor the individual child plus the tool, but the whole cognitive system in the classroom (Newman, 1990; Salomon, 1993). Newman defines the cognitive system:

> The teacher creates a social system in the classroom that supports certain kinds of discourse and activities; students collaborate within the system, contributing observations, answers, and concrete products such as texts, projects, and data. The cognitive system includes the externalized tools, texts, data, and discourse all of which is produced by and for the activities.

Whole-group analysis was chosen as the core mode of data gathering, with attention paid to how all aspects of the learning environment (the group of students, their conversations, and the tools they employed) contribute to successful collaboration.

However, there is an important caveat to this approach. Though many researchers have accepted and supported the notion of studying the collaborative process, they have also noted a problem with this method. Using large groups of students as a unit of analysis is difficult since students frequently separate into smaller subgroups during the collaborative effort, altering the composition of the unit of analysis midstream (Granott, 1998). To alleviate this problem, Granott has argued for a structure of analysis that studies the smallest working unit of students, which she calls the "ensemble", rather than attempting to study the interactions of the whole group. This project proposes a slightly different solution to the problem of group fragmentation. In a Participatory Simulation the very nature of the simulation, analysis, and experimentation is such that every member of the class needs to be participate. Therefore, there is no opportunity for structural fragmentation within the whole group. In fact, on the few occasions when someone in the class is not collaborating in the process, the students call those 'stragglers' back into the whole group. Theoretically, there are legitimate reasons for embarking on a study of the whole class as it is the "ensemble" group in a Participatory Simulation.

The main source of data for the Participatory Simulations project was a complete videotape log of the sessions that, in particular, aimed to capture all of the whole-group conversations. In addition, audiotape backups were made of every session and facilitator logs were kept throughout the project. Students were occasionally asked to write down their ideas about the disease dynamics, and all of those student responses were kept. Video records were logged and transcribed. Forty episodes were chosen as key events, based upon their identification as dense interactional segments. Each of the episodes was coded to identify the presence of four activities: immersion in the simulation, collaborative analysis of evidence, collaborative experimental design and prediction, and negotiation about new vocabulary. The relationship of these measures to the four characteristics defining the learning environment in section 3.0 will be furthered explored in the results section (5.0) of the thesis. The episodes were also coded by a second person in a blind test and the results strongly correlated (.95, .93, .90. and 1.0 for each of the categories respectively).

5.0 Results

5.1 The initial disease simulation

Aside from a very brief introduction to the researcher and the Media Lab, the students' first experience in the Participatory Simulations project was playing a disease simulation game. Each student was handed a Tag and the basic features of the technology were explained, namely that:

- the Tags communicate with one another by infrared, "like a television remote control" so that directionality is important when interacting with another player,
- the number pad displays the number of people each participant has interacted with,
- participants could interact with another player only once, and
- the five LEDs flash red when the Tag is sick.

In addition, the students were given one other guideline for the simulation—they were told that they were free to stop playing anytime they wanted and could do so simply by turning their Tag around to face their stomachs (or turning it off) and sitting down.

The context was set for the first simulation by giving the students a challenge: meet as many people as they could (as kept track of by the number pad) without getting sick. They were told that one of the Tags was contained a virus. As indicated above, the students were told nothing about how the virus moved from one Tag to another, nor were they told anything about the degree of contagiousness, the possibility for latency, or any other underlying rule that could effect the spread of the disease. This information vacuum is fairly uncomfortable and unusual for most students, especially in a science class where the typical mode of behavior is that a student (or a teacher) asks a question and very soon someone provides an answer, the validity of which is almost immediately confirmed or denied by the teacher. In this situation, students' questions about the simulation were not answered. Instead, they were given the opportunity to experience the disease simulation for themselves.

5.2 Immersion in the Simulation

One of the key components of the Participatory Simulation is its ability to give the students a real experience which is mediated by a set of underlying formal rules. One measure of success of the Participatory Simulations, then, is the extent to which students feel as though they *actually* experienced the simulation; in this case, the extent to which they really felt like they were in the midst of a disease infecting the members of their small community.

The following excerpt is from the first five minutes of a pilot Participatory Simulation and gives some of the flavor of excitement and tension that permeates the learning environment.

Sam:	I'm not meeting <u>any</u> of you
Kate:	wait
Sue:	I wanna meet Joe
Lisa:	<u>Joe</u>
Joe:	Do you have (the virus)?
Sam:	She's got the VIRUS
Sue:	No
Kate:	<u>Joe</u>
Kate:	Joe you need
Joe:	whaddaya mean (you have a) blinking red light?
Sam:	she's got the (virus).
Kate:	Joe.
Sue:	what?
Joe:	You have a blinking red light
Sue:	Ooh, I do. Oh oh my god, I've got it!
Kate:	Listen, Joe
Joe:	(to Sue) Let's meet each other. We might as well hang out if we have the virus.

The following episode from the Participatory Simulation analyzed in this project illustrates a similar level of engagement in the activity and willingness of the students to suspend their disbelief and behave as though the simulation activity is real.

Episode 1

42:29	I got it from her (Doug)
42:41	You all got the <u>vi~rus</u>! (off camera)

42:41	I'm dead. (Stacy)
42:53	Oh, you got the virus now. (Doug to Tony)
42:58	(looking at badge) you get [sic] it started. (Tony)
42:59	(singing) I ain't got the vir~us. (Rick singing)
43:00	I'm healthy.
43:02	I don't have the virus. (Meredith holding her badge)
43:40	Who in this room met the most people? (Researcher)
43:42	I have 14, I got 16, I got 13 with no virus, me too, I got 14 with no virus. (chorus)
44:15	I need some medicine. (off camera)

When Stacy exclaims that she is "dead" there is little ambiguity about her complete immersion in the metaphor of this simulation. Similar metaphorical references occur throughout the study, as at 44:15 when a voice off camera declares that he needs medicine.

Engagement in the activity is always an important component of a successful learning environment, as it tends to correlate highly with motivation to solve the problem or learn more. A high level of engagement is present in these activities, but there is another, more subtle point that should be highlighted. The students are actually behaving as though they are sick, even though they are merely wearing Tags that indicate red lights or no red lights. They have been told that one of the Tags had a virus, so the claim is not that it is surprising that they talk about the virus. Rather, the significant occurrence is the extent to which they are fully engaged and immersed in the simulation. They clearly know on one level that this is just a game, but they are engaged in the activity in a profound manner.

This level of engagement permeates the next four days of the research project. As each game unfolds, the students once again have a "real-life" experience of an epidemic in their small community. They do not need to imagine what it would be like for all of them to be struck by some mysterious disease, for in the context of the Participatory Simulation, many of them *have* been struck by that disease. Their task will not be to imagine or mentally construct the dynamics of the situation from a description of a disease, but to figure out what is happening in their community. This powerful, immersive experience is one of the key components of the Participatory Simulations and is integral to the students really feeling as though they have had a real experience.

Though the engagement in the immersive experience is an integral and important component of Participatory Simulations, much of the learning occurs as students are able to step back from their immediate experience and analyze the situation. Ackermann (1996) has described this process as "diving-in" and "stepping-out," as students move back and forth between full immersion in a problem and thinking about a problem. Similarly, Sterman (1994) distinguishes between the features of learning "in" and "about" dynamic systems. The students in Participatory Simulations generally step back from the activity and stop playing the game when a small majority of their Tags is sick. As they finish, students sit down and begin to find out what happened to their classmates. After everyone is done playing, the entire group reconvenes to examine what happened. First, they establish who won (by gaining the highest number of points without getting sick). Then they begin a collaborative exploration into why the game unfolded as it did.

5.3 Gathering evidence to build a theory

Students in the Participatory Simulations projects collaborate with one another in two distinct ways. The first form of collaboration is a data-collecting or evidence-mounting collaboration. The students accumulate data and then begin to make assertions based on the data available. If a student has information that contradicts another student's assertion, that information is offered in response. As the available evidence increases, the potential for collaborative theory-building emerges. In the following episode, students are in the early data-collection phase. This pattern of offering evidence to the group knowledge base is typical after each game. Here the students present their own "data" from the simulation.

Episode 17

11:11	All right, I'm all set; I'm not meeting nobody else. (Liz)
12:50	I'm sick. (Liz)
13:00	Oh, I just boot beeped her. (Rick)
13:04	Liz's the first one, Liz's the first one to get sick! (Stacy)
13:10	Who'd you share with? Do you remember? (Stacy)

13:12	Wait, who was the last one you shared with? (Allison, writing on board)
13:14	Rick. (Liz)
13:17	Wait, you gotta go in order. (Allison)
13:16	OK, look at, Doug, Rick was the last person she shared with. (Stacy)
13:34	It's Rick's fault, it's all Rick's fault. (Liz)
13:35	No 'cause I shared with Rick. (Stacy)
13:36	I shared with Rick too. (Liz)

As different students offer data to the group, like "Rick was the last person she shared with," other students respond, either with other data points from their own experience or with what might be called mini-hypotheses offering a frame of interpretation for the previous data. For instance, Liz says, "It's all Rick's fault" after Liz provides the data point (and Stacy reiterates) that Rick was the last person she shared with. Following this assertion, two people respond with data that indicates this framework might not be robust; in this case because they had each met Rick and were not yet sick.

A similar collaboration happens early in the first game as the students are trying to figure out what happened to them.

Episode 6A

49:00	We should all meet each other. (Rick)
49:23	I met Doug like two minutes before he gave the virus to other people and I didn't get sick. (Joan)
49:33	How do you clear these? (Allison)
49:38	I need a medicine, I need an antibiotic. (off camera)
49:50	Is there anyone who started with the virus other than this guy in the front? (Researcher)
49:52	Doug. (Rick supplying name of guy in front)
49:52	That's just cause Doug's dirty. (Allison)
49:56	Doug didn't start off with the virus. (Joan)
49:59	Who started out with the virus? (Researcher)
50:00	'Cause I met him, I met him. (Allison)
50:00	'Cause I met Doug and I didn't get the virus. (Joan)
50:02	Doug was the second person I met. (Allison)
50:04	I.. I met her and then I just, the virus was just like pop. (Doug)
50:06	I didn't get the virus until I got it from somebody else. (Allison)

Again, there is data presented (some of it before this episode begins) that culminates in the notion that Doug has infected a lot of people. As soon as the hypothesis is restated that Doug may have started out with the virus (49:50) Joan reiterates an alternative hypothesis, “Doug didn’t start off with the virus”, which is subsequently supported by data from four people in this episode.

Two other points of interest emerge in this last episode. First, it is again apparent that the students are still highly immersed in the disease metaphor, even though they are no longer playing the game and are now evaluating its outcome. The students are contributing evidence for whether or not Doug started out with the virus when Allison says, “That’s just cause Doug’s dirty.” Just moments later, Allison is fully involved in the gathering evidence about Doug’s state, suggesting that the experience that the students have had with the disease game is still influential for them, even while they are puzzling over the outcome. The realistic nature of the students’ experience component is significant yet does not seem to prevent them from participating in the intellectual problem solving endeavor. Over time, the number of metaphorical references to the game decrease, though they never dissipate entirely and are still significant even in the very last game.

Also, in Episode 6A the first example of experimental design is uttered. Rick says, “We should all meet each other,” in the first experimental proposal to figure out why some people aren’t sick. (Unlike many scientific learning experiments, his proposal is not solicited by the teacher.) Right now his proposal falls largely on deaf ears. The other students are still engaged in a retrospective analysis of the game. But Rick will come back to his suggestion in the future, and there we will analyze another form of collaborative activity.

First, let’s look at one more episode in which evidence gathering and data analysis is insufficient and the students spontaneously turn to experimental design to solve their disagreement.

Episode 10

00:45	I don't think, you know, because, Andy's not sick right now and he's sharing it with us that are sick and he's not. (Stacy)
00:52	Yeah but it takes a couple of minutes. (Allison)
00:53	But he's not getting...... (Stacy)
00:54	It takes you a couple of minutes (Allison)
00:55	... but he's not getting sick though. (Stacy)
01:03	But it doesn't happen right away (Allison)

(they try to infect Andy and Allison keeps track of the time, counting)

01:20	15 seconds, 25 (Allison)

Again, the students exchange information and build on each other's theories. Here, Allison has a dialogue with Stacy in an attempt to convince her that you can't tell if someone is sick right away. However, exchanging data in this case is not sufficient for Allison to convince Stacy of her opinion. Perhaps Stacy is holding some as yet unarticulated opinion about why Andy is not sick. Without even saying what she is doing, Allison starts counting the amount of time after they try to infect Andy, looking for some data to prove that her assumptions about the underlying mechanisms of the virus are correct.

5.4 Experimental design and execution

This last experiment leads directly into the second form of collaboration, which supports a different activity: now the students are engaged in collaborative experimental design. As they get ready to decide on an experiment to run, the level of collaboration is high, but this time the content is predictive in nature. The students are defining what experiment they want to run to illuminate the underlying rules that govern the viral behavior.

Episode 15

4:45	Do you have a strategy to avoid that [the virus]? (Researcher)
4:44	Stay away from people. (Allison)
4:46	But you don't know who. (off camera)
4:47	That's what makes it confusing. (Allison?)
4:53	I know how we could get it, everyone turn on them badges and just turn 'em around and then whoever has the uh, whoever's thing lights up first. (Rick)

5:06	How ‘bout all the people, each one [has a] partner, and then only meet with one person and whoever gets sick. (Doug)
5:27	Everyone turn their badge around so no one can communicate with them and who ever’s thing turns red first. (Rick)
5:37	But can’t the host not get sick, like the person who has the virus his buttons won’t get red but he could give it to someone else? Yeah, we could pick groups, like um, they communicate with each other, they communicate with two people and if they get sick then these are the people who have the virus. (Doug)
6:05	Go around the room again like we did before and then as soon as your thing turns color, like, yell, out, you know what I’m saying, when it turns color, try to see who was the first person. (Stacy)
6:23	And then we could record, like, who we shared with. (Stacy)

Experimental design is one of the crucial skills of scientific practice. Unfortunately students typically have few opportunities to practice this difficult task, and it remains out of the reach of many science students. Experimenting within a microworld helps students to interact with complex phenomena in domains like geometry or physics in a manner they would not have access to without the computational support of the microworld. However, even those experiments can be quite difficult for some students. Some researchers have focused on ways in which collaboration can increase the value of interacting with a microworld. This added value derives from the richer experiences students can have as they “boot-strap” one another during their explorations. For instance, exploring Newtonian physics may be beyond the reach of an individual learner, but, in collaboration with classmates, the student may be able to do more exploration within the microworld and learn more about the underlying concepts. Even a small community of practice can help students since the aggregate abilities of the group often enable more exploration, more questioning, and more learning. During a Participatory Simulation, the community of learners tackles the difficult tasks of experimental design and execution as a group, leveraging off of the skills of the community to achieve success.

Earlier in this section we saw how evidence gathering and preliminary analysis creates a classroom-wide, knowledge-building community during Participatory Simulations. Here that knowledge-building community ventures into new territory as its members begin to collaboratively speculate about how they might learn more about the environment they're in. In the next section we will look specifically at how the ability to engage in experimental design evolved over time.

Before analyzing that evolution, two minor points should be highlighted. Two short episodes will bring these points to light.

Episode 21

18:20	I think we should just turn ours on and wait and see whoever gets sick first. (Allison)
18:24	THAT WAS MY PLAN!!! (Rick) (leaps out of his chair) You got that on tape right, I said it first! (Rick)
... conducting the experiment...	
19:41	We're supposed to chill. (Rick)
19:58	Allison you wanna exchange? (off camera)
20:00	No, we're not supposed to have anybody. (Allison)
20:30	Everybody's supposed to have zero. (Allison)
20:32	Is everybody supposed to have zero? (Stacy)
20:35	That's what I thought. (Researcher)
22:38	This is my experiment! (Rick)
22:40	Oh, I get it we're trying to see if anybody turns up red. (Tom)
22:59	One minute. (off camera)
23:08	I think we should give it ten minutes. (Allison)

Episode 31

54:18	Oh look, it's red. (Stacy)
54:31	Just only beep her once and that's the only person you meet with is Stacy. (Allison)
54:34	Why?? Then we're all gonna end up with it! (Rick)
54:36	No, 'cause we have to see who's immune. (Allison)
54:37	I'm not going to beep her. (Doug)
54:53	I don't want to beep ~her~.(Rick)
54:54	You have to or else the experiment won't work. (Allison)

In both episodes 21 and 31 there is community negotiation about the design and execution of the experiment. As was noted earlier, the nature of the Participatory Simulation ensures that all of the class members work together. As people become marginalized either because they are confused as to the nature of the experiment or because they are trying to subvert the process, the group pulls them back in. The ensemble size here is the whole class. As Allison explains, "you have to [participate with us] or else the experiment won't work."

Second, episode 21 highlights an important by-product of collaborative experimental design by the students. There is a very high level of pride and ownership about the proposed experiments. The only time during the second phase of the project that the students talk to the camera is in defense of an experiment they proposed, as when Rick declares his ownership of the experimental idea.

So far, we have explored qualitative data in support of three claims: the students are immersed in the simulation, they help each other gather evidence and build theories, and they collaborate to design experiments to test hypotheses about the rules of the microworld in which they are playing. Collaborative experimental design now coexists with collaborative data analysis and the students move back and forth between playing a game, analyzing a previous game and planning their strategy for the next one.

5.5 Progression of experimental design

The students in the Participatory Simulations project were placed in a "life-sized" microworld that presented a pre-constructed phenomenon. They were presented with the challenge of producing a certain outcome—meet a lot of people without catching the virus—and allowed to work together as they sought to figure out what was happening in the simulation. As in traditional microworlds, figuring out the simulation rested on the need to understand the underlying rules of the disease world. The students did this not by learning a symbolic representation but by continuing to experiment within the simulated world until they could reliably predict the outcome of an event based upon the rules they postulated. For instance, at the end of the study, they could predict who would get sick after meeting Patient Zero and how long it would take for those people to get sick.

Learning to probe this microworld to get at those underlying rules is a difficult and challenging task. Over time, the students worked together to create experiments in order to make sense of their observations and experiences in this disease world. They perform these tasks in the context of a community of practice that helps them achieve their goals. A macroscopic look at three of the games they played will show their budding capabilities as they worked to comprehend of the rules of their microworld.

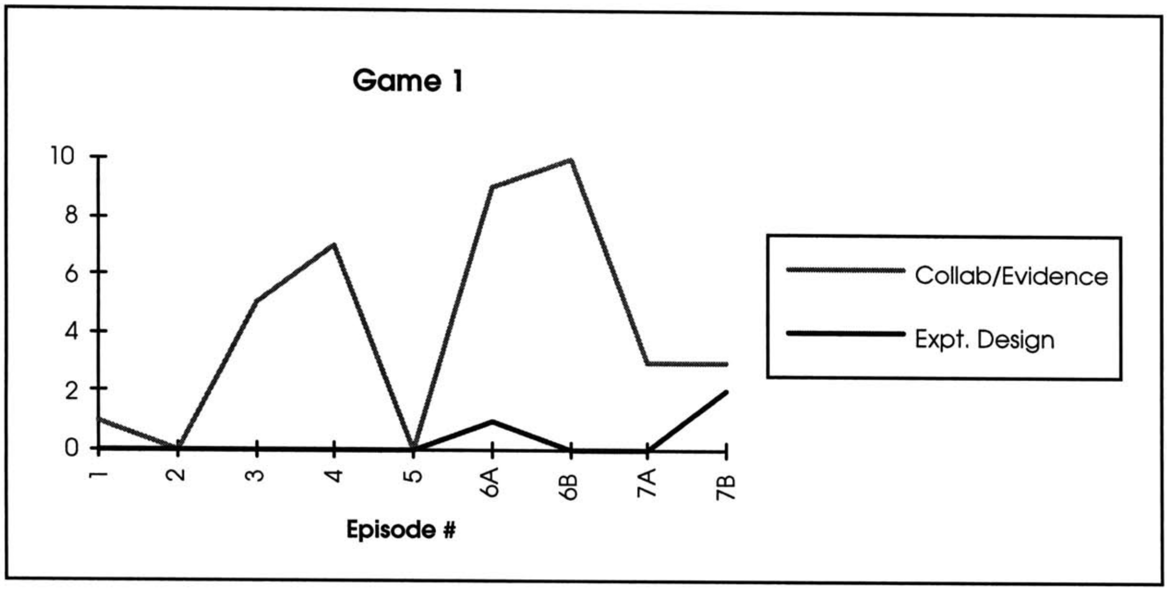

Figure 6: This graph shows the progression of collaborative evidence gathering and experimental design during the first Participatory Simulation game.

In the first Participatory Simulation game, the students' level of collaborative data collection and preliminary data analysis is much higher than their level of experimental design (means: 5.43 occurrences per episode vs. 0.43 per episode). As the students recall the game and try to make sense of it, the level of energy around discussing each individual's experience and comparing "notes" is high. As you can see from Figure 6, the focus on designing experiments to elucidate the dynamics of the system is quite low, almost non-existent in the first game. The students have just been immersed in a microworld in which they have no prior experience. Clearly, sharing experiences takes precedent initially, leaving little cognitive space for other activities like planning new activities. As a result, Game Two follows a very similar pattern, namely, high collaboration in evidence gathering and very little collaboration on experimental planning (means: 5.60, 0.20).

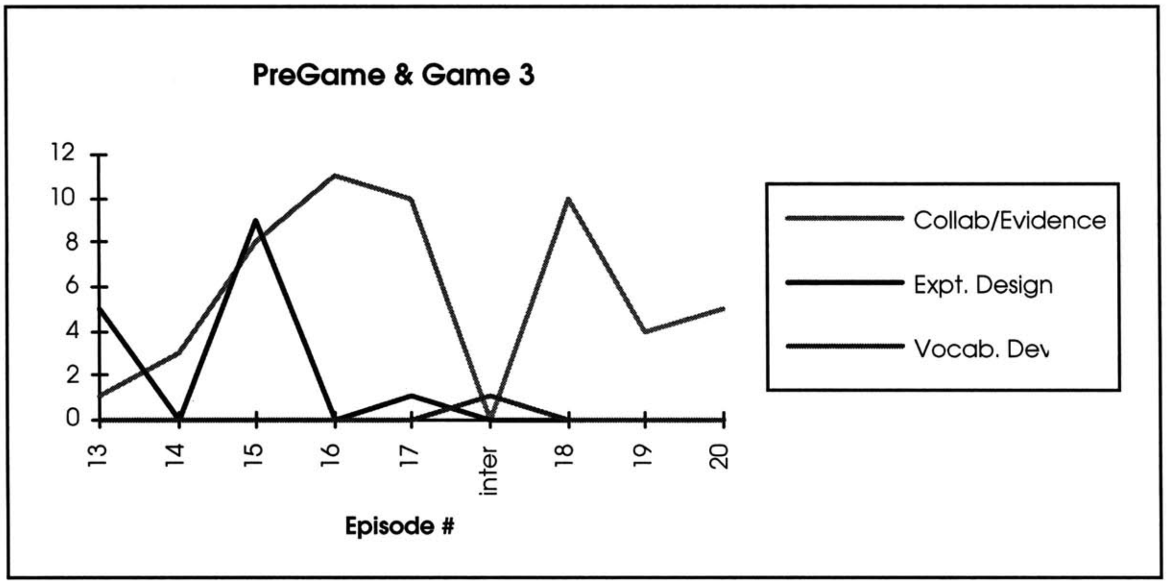

Figure 7: This graph shows the progression of collaborative evidence gathering and experimental design just before and during the third Participatory Simulation game. It also indicates the interlude between episodes 17 and 18 during which students engage in a discussion about defining appropriate vocabulary to describe their experiments.

Game Three takes place on the second day of participatory activities. The characteristics of this game are significant both in the way it differs from the previous games, and in the ways it is similar. In Game Three, the students are fully engaged in figuring out how the virus is spreading. Collaborative analyses of data they have collected and continued accumulation of new pieces of information defines much of the group's activity (mean: 6.50). However, experimental design emerges as a key activity during this game. Unlike the previous games where almost all of the group's focus was directed toward sorting out what had happened during the simulation, the focus has now been broadened to include prospective and predictive hypotheses. Note that this expansion has not been at the cost of evidence-collecting activities, as they remain high (in fact even slightly higher than before) during this game. The students break out of this pattern only once in the interlude between episodes 17 and 18, when they engage in a brief negotiation about how to define the experiment they are designing. This will be examined in section 5.5.

The collaborative experimental planning and execution seen in Game Three leads to two more iterations of the game, each of which retain a similar group focus on data-gathering and experimental design. (means: gathering evidence 5.00, experimental design 3.25) The understanding built in these two games sets the stage for Game Six, the final push to uncover the underlying mechanisms of the viral behavior.

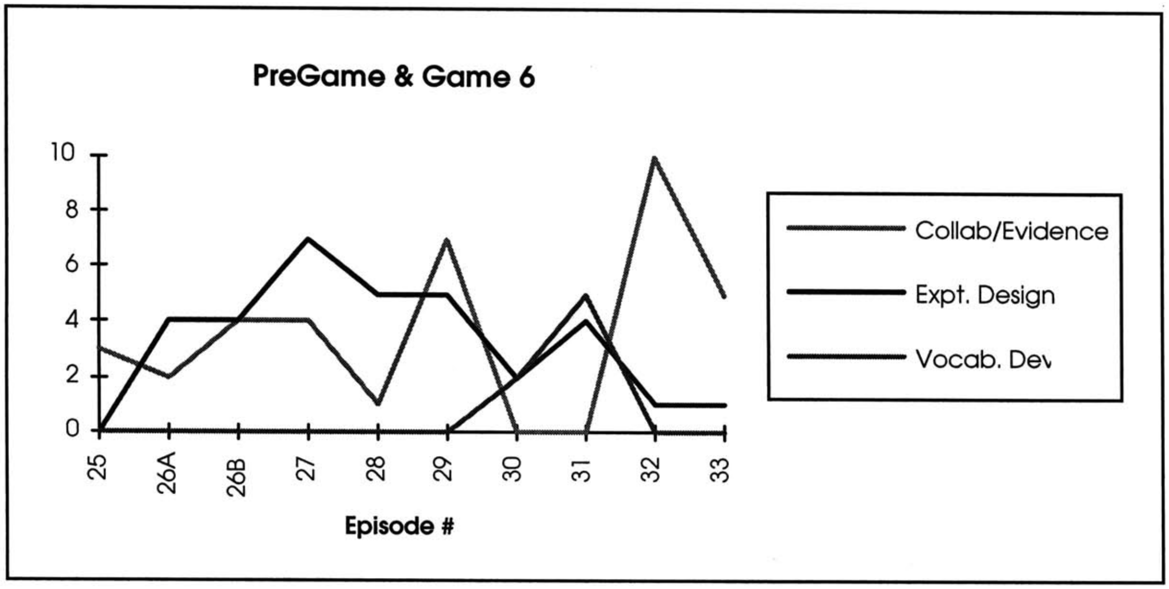

Figure 8: This graph shows the progression of collaborative evidence gathering and experimental design just before and during the sixth Participatory Simulation game. It also shows a discussion about vocabulary definition during episodes 30 and 31.

Game Six occurred on the last day of the participatory activities. The level of group collaboration on experimental design is very high (mean: 3.67) compared with the previous five games. Interestingly, the level of collaborative evidence gathering activities remain high as well (mean: 4.00), indicating that these activities are not mutually exclusive, and may even be supporting one another.[4] The experiments designed and carried out over the course of the six games lead the students to propose a set of rules that, according to their analysis, governed the behavior of the virus simulation. However, finding a way to describe these rules was not a trivial task. In a couple of places, the students' activity slows markedly as they talk about how they should talk about the underlying rules. We see one of those lulls during episode 31 as the students challenge each other about what they mean when they articulate their ideas.

5.6 Developing a vocabulary

The central challenge of Participatory Simulations is to develop an understanding of the underlying rules of the simulation. However, unlike traditional microworlds, Participatory Simulations do not explicitly link the patterns and activities (in this case of the disease) to a symbolic representation of the underlying rules. Therefore, as the students get increasingly involved in collaborative experimental design and the collaborative interpretation of results, they need to find ways to communicate their ideas to one another. The more their ideas are about the underlying rules instead of the experiential component of the game, the harder this communication becomes. In time, they begin to develop a vocabulary to talk about the underlying rules, using the Tags as props to define their comments.

Episode 40	
20:55	It was a pattern like that 20 21 thing. (Tony) The numbers. (Tony)
21:01	It was 1 2 11 21. (Meredith)
21:05	I ~said~ the 21 thing. (Tony)
21:06	It wasn't specific. (Meredith)
21:06	It was specific—you knew what I was talking about. It was specific enough. (Tony)

The Tags enabled the participants to engage in a meta-level conversation around a big idea—the underlying rules of the simulation. In episode 40 two students negotiate about how they want to refer to immunity, trying to determine what utterances are necessary and sufficient to express their ideas. The Thinking Tags serve as conversational props, supporting the definition of a vocabulary to talk about the mechanisms that mediate the observed or experienced phenomenon.

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[4]Though proving a causal or mutually-reinforcing relationship between these activities would require a different method of data collection and analysis.

5.7 Revealing the rules

Participatory Simulations immersed students in the simulation experience and provided a setting for collaborative investigations. During the activities, students worked together to figure out what had happened during the disease simulation and collaborated to design experiments to elucidate the viral behavior. They not only discussed these experiments, but also ran the experiments and collected data. Each successive step helped them to understand the underlying rules of the simulation. Along the way, they developed new ways to talk about the rules of the simulation, sometimes interrupting their analyses to agree on the "proper" way to talk about a rule.

After four days of collaborative work and increasingly sophisticated experimental design, they articulated the underlying rules of the disease simulation,[5] namely:

- The virus is latent (invisible) for approximately three minutes,
- Patient Zero (the host Tag) gets sick after approximately three minutes,
- Any person whose Tag has the virus, even if it is not visible, can infect another person's Tag,
- The probability for infection when meeting an infected Tag is 100%,
- People with Tags numbered 1 or 2 in the ones position (1, 2, 11, 12, 21, etc.) are immune to the virus, and
- Immune Tags are not carriers of the disease.

[5] Since the Tags are fully programmable, these rules could be modified or completely changed for a different Participatory Simulation.

6.0 Design criteria for creating immersive learning environments

As Salomon (1995), Newman (1990), and others have noted, it is difficult to isolate a set of variables which, when altered in a classroom, change the nature of the learning that takes place. This difficulty is certainly illustrated in this project, where the technology mediates a new activity, changes the relationships between the students, alters the very notion of scientific exploration, and becomes a foundation for creating a new vocabulary. In this section we will describe some of the classroom level decisions that were integral to the Participatory Simulations project and look at how those decisions supported and shaped the technology design.

6.1 Encourage similar but non-identical experiences

The activities in Participatory Simulations are designed so that every student has a similar experience that he or she can relate to the whole group. Each student gets their own Tag that behaves in a consistent and (eventually) comprehensible manner. Because we designed a completely distributed simulation system, no single Tag is "running" the whole simulation and no one student's Tag is more important that anyone else's Tag. (With the possible exception of Patient Zero who begins the infection, but that designation is chosen randomly at the beginning of each game.)

However, not every experience is designed to be identical. Students whose Tags are immune to the virus have experiences that differ consistently from those of their classmates. Students who elect to behave in a particular manner—perhaps meeting a lot of people or perhaps interacting with no one at all—also have incongruous experiences. The asymmetry of experience is created not by the differing talents of the students but by their differing experiences of the activity. In order to decipher the underlying mechanisms of the whole virus simulation, students must first develop an understanding of what happened to them and then listen to what happened to other people. As these descriptions build one by one, the students begin to develop an understanding of the simulation as a whole. The experiences that differ from the mainstream can then be identified as outliers, and alternative hypotheses can be proposed for those data points.

The combination of everyone having an inherently significant experience bonded the whole class into a learning group or "ensemble." The fact that not every experience was identical reinforced the need to listen to and account for each and every student's experience, not just extrapolate from one personally-meaningful data point. Participatory Simulations enable a new kind of collaborative learning in which every child's experience builds towards an understanding of the whole. The process involved in building this understanding pushes students to make their thinking overt (Brown & Campione, 1990) as they explain their ideas and predictions to their classmates. This environment is particularly rich for looking at the process of collaboration because the technology supports and mediates a problem context that involves the whole group, allows face-to-face collaboration, and provides a computational substrate for experimental design and execution.

6.2 Keep the technology unobtrusive

As in earlier work with Thinking Tag technology, care was taken to preserve natural social interactions, using the Tags to augment, not take over, communication and collaboration. In the Participatory Simulations project this design choice accomplished two important goals. First, the Tags did not get in the way of the natural communication between students. If anything, the Tags served to enhance that communication as the students developed a vocabulary for discussing the underlying rules. Second, though the technology was quite unobtrusive, the students became deeply engaged in the disease experience.

Unlike many computer-based collaborative environments, Participatory Simulations fully support natural communication among students. Participants use voice, gesture, and expression to communicate with one another, rather than sharing information through text and images on-screen. Students' interactions are not blocked or impeded by large monitors or awkward technology configurations. Moreover, the minimal technology display seems to encourage students to use their own imagination and experience during the activities. The students were able to use social cues and knowledge about each other to enhance their engagement in the game. Recall Rick's pride that he wasn't sick, "I'm the man... that's right, I'm a clean head again... You all want to be like me." Or the initial suspicion that Tom was the first carrier. "Who started out with it? I think Tom did. Why? Because...look at him. (laughter) Sometimes you can tell like that." Or the notion that Doug started out with the virus because he's "dirty." On the last day of the project, two students recalled their experiences:

Episode 38

13:00	You don't feel good when you have the virus unless there's something not working up there.... Yeah, 'cause I didn't like it, I got it [the virus] when I wasn't even in the room and that was just upsetting to me. It's a hard thing to deal with. (Tony, serious)
(laughter in the room)	
13:15	It was. (Tony)

Episode 39

17:01	Say you have HIV or something, a virus, and it don't show up in your system right away, you could give it to someone else without knowing. (Doug)

These comments are the result of wearing a small Tag that has five LEDs and a double digit number display. The students who participate in "life-sized" simulations use the framework of the simulation, their own imagination, prior knowledge, and other past experiences as they become immersed in the simulation. They feel as though they are really sick even though there is very little explicit computational support for the metaphor of the game.

The unobtrusive nature of the Tag technology supports rich, collaborative interactions among a large group of students. The Tags' minimal display does not impair the students' ability or willingness to become immersed in the simulation. This may have implications for designing engaging educational technology, the budget for which rarely rivals that of pricey virtual reality games where fancy graphics and head-mounted displays provide all of the context for a "virtually real" experience.

6.3 Add coherent, consistent rules to the experiential world

Even though the Tags did not constrain the communication or the behavior of the students, they provided a tremendous amount of structure in the environment. The Tags carried the underlying rules of the simulation into the students' world. In some sense, the Tags transformed the students into agents in a microworld, even as they allowed the students to retain their own personalities. The Tags were able to mediate the simulation experience without constraining the students' behavior.

Bringing a microworld into the realm of students' experience enabled the students to explore the underlying formal structure of that world without abandoning their own perspective. They made use of the consistent behavior of the Tags as they designed experiments to understand the mechanisms that governed the viral behavior. Toward the close of the project, they even used the Tags as props to support a new vocabulary as they spoke about those rules. Each of these components of the Participatory Simulations project arose because the Tags created an environment that was initially mysterious but upon further reflection and action became transparent. The use of the Tags allowed the students to reach transparency through a new path that avoided formal, symbolic notation, instead drawing upon the students' own personal experiences and their own systematic explanations of those experiences.

7.0 Conclusions

Participatory Simulations use new technology to create a new kind of collaborative learning environment, adding to the current body of work in CSCL. Participatory Simulations facilitate an experience mediated by underlying rules that are consistent and comprehensible. The experience can later be reflected upon, enabling learners to build links between the experience and the underlying rules. This work suggests that new technologies provide an opportunity to re-evaluate the role that experience can play as a scaffold for understanding the mechanisms that govern patterns and processes in the world.

In a Participatory Simulation, thinking about changes in yourself and your world is the same as thinking about changes in the behavior of agents and the outcome of a model. Recognizing a pattern that describes the experience of you and your best friend is the same as recognizing a pattern in a model. Participatory Simulations provide a direct connection between experience and a system based on underlying rules, similar to a microworld. Examining this new kind of microworld can lead to the development of an understanding of the rules that govern those experiences. The Participatory Simulation is in some sense a "middle" step between normal, non-mediated experience and underlying rules. The fact that this "middle" step is connected very closely to participants' experiences gives those participants a fluid way to move from experience to understanding the mechanisms driving the experience.

Computers have been used to build bridges between experience and formal symbolic representations. Participatory Simulations construct an environment in which people can move back and forth between their own experience and their developing understanding of the underlying mechanisms that influence their experiences. Importantly, formal, symbolic representations are not provided. Instead, children create their own vocabulary to discuss the underlying rules. They propose and negotiate this vocabulary at the precise moments in their experience when they need a new way to express their ideas. The analysis presented in this thesis suggests that this process is quite challenging, and the iterativity of the environment increases the students' ability to move toward developing this vocabulary. This path differs from the more conventional computational bridges that use formal, symbolic representation to describe the underlying rules.

8.0 Future work

- Studying how learners define a new vocabulary:

In this study, we saw that students used their experiences during the Participatory Simulations to develop a new vocabulary for discussing the simulation and its underlying rules. In pilot studies for this project, students engaged in many more vocabulary negotiations than this group of students. Also, students frequently used the Tags as props to indicate another person's state, refer to a previous action, or illustrate a hypothesis. Further research is needed to establish why some students engage in more vocabulary negotiation and definition than others. Such work should include a clear categorization of the types of new vocabulary defined and an exploration of the news forms of meaningful gesturing employed during Participatory Simulations.

- Exploring the role of multiple representations, in multiple media:

During Participatory Simulations, students are encouraged to use their own experiences to build an understanding of a dynamic system. During a disease simulation, students sometimes line up next to the person who they *believe* infected them with the virus. After further exploration, they "re-shuffle" when they have discovered the person who *actually* infected them. Can this "living" tree diagram of the virus infecting a small community lead to a clearer understanding of the spread of the disease? How might other representations help students build an even better understanding? A project is planned to explore how multiple representations, designed both by students and researchers, can lead to a more integrated understanding of simulations. We have developed an on-screen simulation program that takes in data from Participatory Simulations and facilitates multiple representations and further experimentation. This link between data gathered in a Participatory Simulation and data manipulated on-screen provides a new opportunity to observe how innovative tools can enable children to bridge the gap between their experience and more formal models of systems.

- Characterizing the roles of individuals:

This study looked specifically at the collaboration among the whole group or "ensemble," uncovering many of the aspects of collaborative learning in an immersive environment. However, data collected for this study also strongly indicated that individuals in the class played a variety of roles in initiating and maintaining that collaboration. For instance, some students give answers while others pose questions; some open lines of inquiry while others declare the "consensus" decisions; some students participate all of the time (often finding their ideas ignored) while others wait until just the right moment to offer some evidence. Future research should probe the roles individuals assumed and the ways in which those roles influence both the class activity and the individual learning.

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