Participatory Simulations:

Building Collaborative Understanding through Immersive Dynamic Modeling

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Abstract

This article explores a new way to help people understand complex, dynamic systems. Participatory Simulations plunge learners into "life-sized," computer-supported simulations, creating new paths to scientific understanding. By wearing small, communicating computers, called Thinking Tags, students are transformed into "players" in a large-scale microworld. Like classic microworlds, Participatory Simulations create a scenario, mediated by a set of underlying rules, that enables inquiry and experimentation. In addition, these new activities allow students to "dive-into" a learning environment and directly engage with the complex system at hand. This article describes and analyzes a set of Participatory Simulations that were conducted with a group of high school biology students. The students' experiences are tracked from their initial encounter with an immersive simulation through their exploration of the system and final description of its underlying rules. The article explores the educational potential of Participatory Simulations. The results of this pilot study suggest an opportunity to further investigate the role that personal experience can play in developing inquiry skills and scientific understanding.

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 stare intently 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 playing the latest simulation game—a sort of 'SimVirus' or new virtual reality 'Outbreak.' 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." Children playing such a game would observe the results on screen and then decide how to use that information to better understand the simulation model.

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. However, the game described above is not played on a computer, at least not a traditional computer. This article explores Participatory Simulations, in which students become players in unique, "life-sized" games that are 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 (National Committee on Science Education Standards and Assessment, 1996; Project 2061, 1993), this project explores how learning takes place in the environment created by a Participatory Simulation.

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 merely part of examining a computer model, they are part of discovering the underlying mysteries of their very own viral epidemic.

Designing Experiences

There is a long history of theoretical claims that children construct their own knowledge through experience (Dewey, 1916; Dewey, 1988; Montessori, 1912; Papert, 1980; Tanner, 1997). Many educators have taken up the task of designing educative experiences, often focusing on selecting or creating particular materials to enable an experience. When developing his concept of kindergarten, Friedrich 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).[1] Much of his notion of kindergarten focused on how the orderly delivery of the gifts would enable children to build knowledge in a coherent fashion. Years later, Vygotsky wrote extensively on the notion that tools (like Froebel's gifts) could enrich and broaden both the scope of activity and the scope of thinking of the child (Vygotsky, 1978). Other researchers have even speculated about the ways in which the objects present in the environment could actually induce development (Fischer, 1980).[2]

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[1] See also (Lillard, 1972) for related work.

[2] For another perspective on the importance of tools in the development of understanding see (Norman, 1993).

Not surprisingly, computers fit right into this lineage. Even before the prevalence of personal computers, Seymour Papert envisioned a future in which computer-based tools would provide children with a whole range of transformative developmental experiences (Papert, 1980). He imagined that constructions within these powerful computing engines would become fodder for children's imaginative and intellectual ruminations, much like gears (his own childhood tool) had become for him. The fact that computers could take on so many different roles, potentially a role per child, was especially exciting.

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 alternate realities (Bruckman, 1998); computer-based modeling environments enable the design and construction of complex paper sculptures (Eisenberg & Eisenberg, 1998); microcomputer-based labs facilitate children's collection of scientific data (Tinker, 1996); and Newtonian-based environments allow exploration of the laws of physics (White, 1993). Each of these computerized tools supports exploration, investigation, or creation—activities central to an educative experience. The next section describes microworlds, the computer-based tools that provided the conceptual and computational frameworks for the development of a new class of educational experiences called Participatory Simulations.

A Computational "Sandbox"

Microworlds were originally conceived to give children a sort of computational sandbox—a world in which they could manipulate "objects" on the computer screen. 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 two pebbles be if they are meant to represent a prince and a princess? A computerized sandbox offers more than just a sandbox on a screen. In a microworld—as in the real world—a child can take actions that have discernible effects on the world. But in a microworld, the child also has some access to the formal rules that govern his actions. Microworlds offer a non-formal entry into a world based on formal, logical constructs.

Picture a girl playing with a toy horse in her room. She can move the horse around and even have it "talk" to other animals in the barnyard. The horse might "gallop" and "trot" as she alters the speed with which she flies the horse around her play space. In a microworld, her horse could still move around in space, talking to other animals, but she might begin to investigate the mathematical relationship between the horse's two speeds. Depending on the microworld, the computer might even show her an equation that relates those speeds. Or she could make the galloping speed dependent on the trotting speed. Certainly, she could perform similar mental operations in the real world, but the microworld can provide a seamless transition from the non-formal, naïve operations in the real world to the formal descriptions and investigations of those operations in the microworld. In fact, research has suggested that microworlds whose formal descriptions closely mirror children's experience with patterns and activities can be better learning environments (diSessa, 1988).

Most often, a microworld focuses on a specific set of formal rules, constraining the types of actions a child can take but providing an opportunity to learn more about the rules governing those actions. Roschelle (1996) describes one such learning activity, during which two girls build up an understanding of the Envisioning Machine, a microworld that facilitates exploration of velocity and acceleration. Like many microworlds, the Envisioning Machine provides "an intermediate level of abstraction from the literal features of the physical world" (p. 241). The computer becomes a bridge linking the patterns and activities in the microworld (in this case, motion of a ball or particle) with the formal expression of those patterns and activities (arrows representing velocity and acceleration), by connecting pattern and activity to representations of the underlying processes. This bridge enables children to interact with both the processes and patterns they observe and the formal systems that govern those patterns and processes. Much as Froebel's gifts facilitated specific activities and, in so doing, helped children develop new understandings, microworlds can broaden the range of activities and thoughts in which children can engage.

Benefits of microworlds.

Teaching often involves creating and organizing special experiences to help children learn certain ideas. The flexibility of microworld environments opens up the range of possible experiences that can be created. Some researchers have claimed that "the computer is… more flexible and precise in crafting experiences that can lead to essential insights" (diSessa, 1986, p. 224). Teachers and researchers have constructed microworlds that make possible countless experiences, from exploring geometric relationships to building interactive river ecosystems. For example, different microworlds enable children to focus an exploration on particular aspects of physics (The Envisioning Machine), mathematics (Logo), or politics (SimCity). One class of microworlds, which enable focused exploration of complex, dynamic systems, has gained mainstream popularity in the past few years. Game software like SimCity (1993) and SimLife (1992) helped generate popular interest in complex systems. Programs like Model-It (Jackson, Stratford, Krajcik, & Soloway, 1994), Stella (Roberts, Anderson, Deal, Garet, & Shaffer, 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.

Microworlds let children experiment with real concepts in play space, or as Pufall (1988) said, they create "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" (p. 29). With microworlds, learning experiences are no longer constrained by what the real world has to offer. We can both limit and augment the real world, sometimes creating simplified spaces for exploring complex topics, other times creating wholly new experiences on-screen. Pufall (1988) further speculated that the new interactions microworlds enable might "alter children's patterns of development, by allowing [them] to interact in ways [they] cannot interact with the 'real' world."

Building on microworlds.

Microworlds introduced many benefits for learning and presented some new challenges as well. Without trying to exhaustively cover the benefits of learning in the real world, it is worth mentioning that there are human ties to interactions in real space that are lost in cyber-learning. Though some users become enamored of the machine (Turkle, 1984), others feel distanced from the patterns and processes they observe on a computer screen. For some people, this distance leads to a general distaste for the 'cold,' unemotional world of computing (Turkle & Papert, 1992). Others are inclined to believe everything they see on a computer, not questioning the validity or appropriateness of simulation results. Sociologist Paul Starr (1994) witnessed one user's lack of intellectual curiosity about the underpinnings of SimCity and another group's disinterest in rigorously questioning the assumptions underlying a computer model designed to forecast future health care costs. In SimCity, the underpinnings of the model are hidden from the user, perhaps stifling curiosity. But the assumptions in the health care model were readily accessible, suggesting that developing a full understanding of a computer model is a formidable task.

As much research on microworlds has shown, these challenges are not insurmountable. Many microworld environments engage students in deep reasoning and sophisticated analysis (e.g., Eylon, Ronen, & Ganiel, 1996; Goldman, 1996; Papert, 1980; Roschelle & Teasley, 1995; Rothberg, S., & Awerbuch, 1994; Schoenfeld, 1990; Tabak & Reiser, 1997; White, 1993). Microworlds enable a diverse set of experiences, encouraging children to broaden the scope of their intellectual investigations. Effective microworlds don't turn learners' "experience[s] into abstractions. [Instead, they turn] abstractions, like the laws of physics, into experience" (diSessa, 1986, p. 212). By actualizing these experiences, microworlds enable learners to directly experience simulations. Or, more precisely, they enable users to enjoy experiences with those simulations that are as direct as we can make them (diSessa, 1986).

In the past, direct interaction with a simulated environment meant manipulating agents or parameters in a microworld or controlling an avatar in a virtual world. New technology allows us recast the notion of "directly" interacting with a computationally simulated experience. We can now deploy simulations in the real world, facilitating a more personal experience for learners. Our aim is that, just as microworlds have greatly enhanced the learning experiences available to students, Participatory Simulations will provide another range of learning experiences, upon which students and teachers can draw.

Another Way to Learn from Experience.

Participatory Simulations facilitate another way for learners to collaboratively investigate the relationship between patterns and processes in the world and the rules that give rise to those patterns and processes. Participatory Simulations build on the characteristics of microworlds, in which models can be executed, and augment them with the affordances of real world experience, enabling learners to become the participants in computer-supported simulations of dynamic systems in real space. Small, distributed computers create a life-sized microworld by deploying consistent, computational rules in real space. Learners can experience and influence this simulation directly. This interaction, though still mediated by technology, is qualitatively different from other technology controlled role-playing games that facilitate interaction through avatars or with the components of a microworld. Participants' personal connections to the educational situation enable them to bring their previous experiences to bear during the activity, establish strong connections to the activity and the other participants, and, we hope, draw upon their experience in the future.

Participatory Activities

The Participatory Simulations Project investigates how direct, personal participation in a simulation leads to a rich learning experience that enables students to explore the underlying structure of the simulation. The idea to use direct, personal participation to help children (or learners) gain a new perspective or build a better understanding is not a new one. Dewey emphasized the value of personal participation in educative experiences throughout the curriculum. 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 simulate a debate on the future of the logging industry. This debate gives the participants a way to represent the characters and think about how the various characters might feel about an issue.

Activities like these 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 attempt 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.

Researchers have attempted to connect personal and physical interactions to underlying (non-human) mechanisms in a variety of ways. Papert (1980) 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. Resnick and Wilensky (1998) expanded upon this idea, involving large groups of people in activities to help them gain a richer understanding of the rules governing emergent systems. Recently, Wilensky and Stroup (1999) developed a network architecture that gives students control over individual agents in a simulation environment. Researchers in systems dynamics also use group activities to help learners develop systems thinking capabilities (Booth Sweeney & Meadows, 1995, 1996; Meadows, 1986; Senge, Roberts, Ross, Smith, & Kleiner, 1994). Participatory Simulations build on microworlds and these group activities, using wearable computers to create an explicit link between personal experience in real space and the underlying rules that mediate those experiences (Colella, 1998; Colella, Borovoy, & Resnick, 1998).

The Participatory Simulations Project

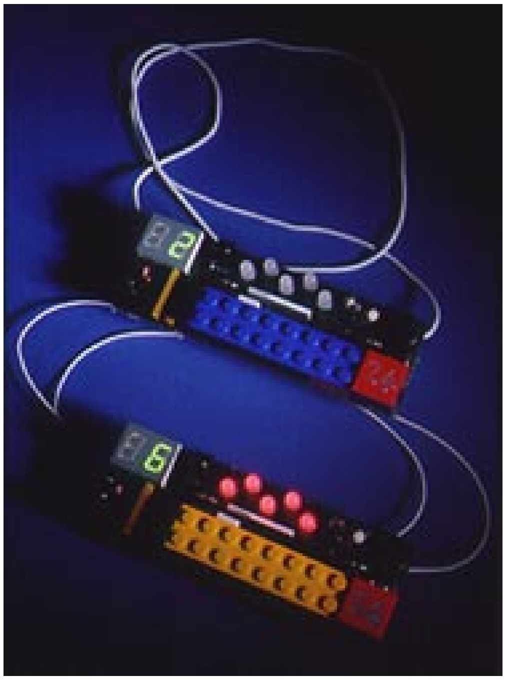
The Participatory Simulations Project looks specifically at how a new kind of learning environment can motivate learners, facilitate data analysis, collaborative theory-building and experimental design, and lead to a richer understanding of scientific phenomena and the processes of scientific investigation. By involving a large number of students (typically between 15 and 30) in a physical experience, the project brings a microworld off of the computer screen and into a child's world. The Participatory Simulations Project is an extended research endeavor, studying the use of personal exploration of computer-supported environments in science learning. Thousands of people have participated in various activities at schools, in workshops, and at conferences. This article reports on a three week long pilot project at a local high school.

Technological Support

We use small, wearable computers called Thinking Tags to enable direct participation in the simulation. The Tags collect information for the participants (like how many other players they have met) 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, which focuses on connecting users to an external network like the web, the Tags connect all of the participants in their own discrete network, which facilitates inter-user connectivity and 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. Participants become players in a computationally-mediated 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, McDonald, Martin, & Resnick, 1996). The Tags are used to transform each participant into an "agent" in a simulation of a dynamic system. In these decentralized simulations, no one Tag acts as a server and no large (traditional) computer is necessary to run, experiment with, or analyze the system. We developed a new version of the Thinking Tags[3] to facilitate collaborative analysis of many iterations of the simulation. 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, Martin, Resnick, & Silverman, 1998; Borovoy et al., 1996; Ishii, Kobayashi, & Arita, 1994; Ishii & Ullmer, 1997).

Like the original Thinking Tags, the Tags built for Participatory Simulations are complete, albeit miniature, computers with input and output devices and displays for the user. Each Tag possesses an infrared transmitter and receiver, allowing it to dynamically exchange information with all other Tags in the simulation. As the simulation is running, the Tags are constantly exchanging information via infrared, though this exchange is invisible to the participants. The Tags have two display devices, a double-digit number pad and five bicolor LEDs (See Figure 1). 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 an input device, allowing users to attach small tools to their Tags and enabling them to "dial-in" information or change the program their



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

Tag has met six people and is sick, as indicated by the five red LEDs.

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.

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 Study 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 different people each participant has interacted with, 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 (kept track of on the number pad) without getting sick. They were told that one of the Tags 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 affect the spread of the disease, leaving them in an ambiguous situation. None of the students' questions about the behavior of the virus was answered. Instead, they were given the opportunity to experience and explore the disease simulation for themselves.

Participants

***number of girls & boys & socioeconomics at end of this section

This Participatory Simulations Study took place in a public high school classroom. 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 devoted to activities associated with the Participatory Simulations Study. The chosen Biology class consisted mainly of tenth grade students.

Sixteen students participated in the study. The teacher also participated in the activities, and on day four a student teacher observed the class and participated in the activities. The researcher (author) was the facilitator of the classes. In addition, two students videotaped the activities.[4]

Activities

In the Participatory Simulations Study, students participated for 45 to 55 minutes on each of four days and 90 minutes on the last 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, three, and four (phase 2) students participated in disease simulations, or "games," and analyses of those simulations. This phase had three distinct components: the initial disease simulation, the discussion of that simulation, and the development and execution of experiments to test hypotheses about that simulation. The students completed six disease games 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 Study and asked to participate in one final simulation game.

Data Collection

Bringing new computational tools into a classroom can fundamentally alter the structure of the class's interactions. The unit of analysis in the Participatory Simulations 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 (p. 187).

During the Participatory Simulations Study, attention was paid to how all aspects of the learning environment (the group of students, their conversations, and the tools they employed) contribute to building scientific understanding.

This study analyzed conversations and explicit collaborative discussions during the activities. The main source of data for the Participatory Simulations Study 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 simulation

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[4] One student was a member of the Biology class who preferred to not be filmed for religious reasons and the other

dynamics, and all of those student responses were kept. We examined the data to find evidence of our four main aims: during the activities, students became engaged in the simulation; students were able to identify and analyze evidence; students were able to design experiments, predict outcomes, and run experiments; and students were able to carry out their investigations in a scientific manner.

Results

Immersion in the Simulation

In the Participatory Simulations Project, we aimed to motivate students by giving them a real experience that 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, we can judge the experiential quality of the simulation by observing the extent to which students suspended their disbelief and acted as though they were in the midst of an epidemic striking the members of their small community.

The following episode depicts some of the excitement and tension that permeates the learning environment:

Episode 1

Doug:	I got it from her.
Student:	You all got the virus!
Stacy:	I'm dead.
Doug:	(to Tony) Oh, you got the virus now.

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was a classmate from a different Biology class.

Tony: (looking at Tag) You got it started.

Rick: (singing) I ain't got the virus.

Student: I'm healthy.

Meredith: (holding Tag up) I don't have the virus.

Researcher: Who in this room met the most people?

Chorus of students: I have 14, I got 16, I got 13 with no virus, me too, I got 14 with no virus.

Student: I need some medicine.

Students display a robust and persistent willingness to suspend their disbelief and behave as though the simulation activity is real. The learning environment promotes a strong connection between the students and the simulation. When Stacy exclaims that she is "dead," she is not talking about an external agent or avatar—she is talking about herself in the simulation. Similar references occur throughout the study, as when a student declares that he needs medicine.

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 invading their small community. Their task is not to mentally construct the dynamics of an epidemic from a written description or a set of equations. Instead, they need to figure out what is happening in their community. The activity "arouses curiosity, strengthens initiative, and sets up desires and purposes" in the students, propelling them to develop an understanding of the simulation environment (Dewey, 1988, p. 20). This compelling, interpersonal experience is one of the key components of the Participatory Simulation and sets the stage for the learning activities that follow.

Though engagement in the immersive experience is an integral and important component of Participatory Simulations, the immersive component per se does not determine the activity's educational value. The experience's potential for leading to growth rests on its ability to allow the students to problematize their indeterminate situation (and later to inquire into its underlying structure). In this case, considerable 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.[5] Many scientific problems offer the chance to step outside of the problem and think clearly about it. Few problems that are appropriate for study at a high school level offer the chance to dive so convincingly *into* a problem. Participatory Simulations create a unique opportunity for students to enjoy both of these important perspectives during the processes of defining and solving problems.

The notion of diving *into* a scientific problem in order to better understand it has not always been highly valued by researchers. The scientific community has traditionally valued detached, objective modes of experimentation, at the expense of more "connected" methods; however, some examples from scientific practice indicate that a revaluation of connected science may be in order.[6] Participatory Simulations can bring connected science to the classroom without forcing students to abandon the exploration of scientifically important problems. As students collect data and design experiments, they remain in touch with the problem at hand. A non-trivial characteristic of the Participatory Simulations environment makes this connection possible—the students are collecting data about and experimenting on their own behavior.

Problem Definition and Hypothesis Construction

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[5] See also (diSessa, 1986).

Like many microworld designers, we wanted to create a learning environment that enables students to define problems and construct testable hypotheses. At the close of the first simulation, there is no clearly defined problem for the students to explore, but they are certainly in a problematic situation. Almost all of the students in the class are sick—a surprising outcome for many of the participants who thought that they had avoided the virus. The facilitator asks if there is anyone in the class who managed not to get sick. The students begin ‘comparing notes’ in an attempt to explain the outcome of the simulation.

First the students accumulate data, and then they begin to make assertions based on the available information. Some of the students’ initial assertions are hypotheses about *why* something happened, some are suggestions about *how* they could prove or disprove a particular hypothesis, and others are ideas about *what* problem they should be investigating in the first place. Students offer supporting evidence for or contradictory evidence against many of these assertions. As the available evidence accumulates and ideas proliferate, the potential for constructing testable hypotheses about the viral behavior grows.

In the following episode, students are presenting their pieces of data from the simulation. Notice that data in a Participatory Simulation are really observations about a student’s behavior or state during or after the game.

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[6] See (Keller, 1983) for an example of how “diving-in” to a problem can yield innovative and previously unimagined solutions to scientific questions and (Wilensky, 1993) and (Wilensky, in press) for discussions of connected mathematics and science.

Episode 2

Rick: We should all meet each other.

Joan: I met Doug like two minutes before he gave the virus to other people and I didn’t get sick.

Allison: How do you clear these?

Student: I need a medicine, I need an antibiotic.

Researcher: Is there anyone who started with the virus other than this guy in the front?

Rick: Doug. (Supplying the name of the guy in front)

Allison: That’s just ‘cause Doug’s dirty.

Joan: Doug didn’t start off with the virus.

Researcher: Who started out with the virus?

Allison: ‘Cause I met him, I met him.

Joan: ‘Cause I met Doug and I didn’t get the virus.

Allison: Doug was the second person I met.

Doug: I... I met her and then, I just, the virus was just like pop.

Allison: I didn’t get the virus until I got it from somebody else.

Here data is presented (some of it before this episode begins) that culminates in the notion that Doug has infected a lot of people. But the students’ suggestions are not especially focused on running experiments or testing hypotheses. When the researcher restates the question, “Who started out with the virus?”, the students continue offering suggestions and ideas but do not respond directly to the question.

It is still apparent that the students are still highly engaged in the disease metaphor, even though they are no longer playing the game and are now evaluating its outcome. The students are busy contributing evidence about whether or not Doug started out with the virus when Allison says, "that's just 'cause Doug's dirty." Clearly, Doug's personal behavior has nothing to do with this particular simulation (and her characterization may not even be accurate), but for Allison it feeds into the connection between the experience and her own feelings (in this case, about Doug). Yet, this interaction between the students and the experience does not prevent them from participating in the more objective problem-solving endeavor. Just moments later, Allison is fully involved in gathering evidence about Doug's state. Students are able to "dive-in" and "step-out" of the problem throughout the Participatory Simulation, solidifying their connection to the problem *and* facilitating their scientific discoveries throughout the investigation process.

A later episode reveals the students' more structured attempts to test the validity of the proposition that a person could be infected by the last person he or she met:

Episode 3

Liz: All right, I'm all set; I'm not meeting nobody else.
Liz: I'm sick.
Rick: Oh, I just boot beeped[7] her.
Stacy: Liz's the first one. Liz's the first one to get sick!
Stacy: Who'd you share with?[8] Do you remember?
Allison: (While writing on the board) Wait, who was the last one you shared with?
Liz: Rick.
Allison: Wait, you gotta go in order.
Stacy: OK, look at, Doug, Rick was the last person she shared with.
Liz: It's Rick's fault, it's all Rick's fault.
Stacy: No 'cause I shared with Rick.

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[7] Because the Tags make a tiny "beep" each time they interact with another Tag, some students began describing a meeting as "beeping" or "boot beeping." This language was laced with innuendo about the type of interaction that students felt the Tags were simulating.

Liz: I shared with Rick too.

As students describe their observations, like “Rick was the last person she shared with,” others respond, either with data from their own experience or with hypotheses that might provide an interpretive frame for the previous data. For instance, Liz hypothesizes that “it’s all Rick’s fault” after a number of observations that sick people had recently shared with Rick. This interpretive frame turns out to be inadequate to explain everyone’s experience. Two students quickly rebut Liz’s hypothesis with observations that they had each met Rick and were not yet sick.

At this point, students converge on a few problematic issues in their situation that they would like to solve, including discovering the identity of Patient Zero (the person who started out with the virus) and describing the way that the virus moves from one person to another. Their earlier, ill-structured presentation of evidence fragments gives way to a more systematic collection of evidence that might suggest which hypotheses warrant further investigation. The Participatory Simulation provides a setting for the students to engage in inquiry. Their pattern of inquiry is consistent with the notion that ideas lead to more directed observation, which in turn brings new facts to light and suggests fruitful directions to pursue (Dewey, 1938/1998b).

Experimental Design and Execution

In addition to enabling students to identify problems and construct hypotheses, we designed the Participatory Simulations environment to facilitate experimental design and execution. Students explore the underlying rules of the simulation by altering their own behaviors and observing the effects of those alterations on the dynamics and outcome of the simulation. Like scientists probing

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[8] “Sharing with” is another way that students talk about meeting one another.

a new domain, the students progressively develop a keener sense of the kinds of outcomes they can produce and begin to propose more specific actions, which they feel will shed some light on the disease dynamics. Their "observation of facts and suggested meanings or ideas arise and develop in correspondence with each other. The more facts of the case [that] come to light in consequence of being subjected to observation, the clearer and more pertinent become the conceptions of the way the problem constituted by these facts is to be dealt with" (Dewey, 1938/1998b, p. 173). Their suggestions become ideas that, when examined in reference to the situation, engender the capacity to predict and test solutions to their problematic situation.

This section describes the students' experimental design and execution in a Participatory Simulation. Just as their descriptions of the experimental state during the data collection phase were about *their own* state, their experimental design involves varying *their own* behavioral patterns to elucidate the viral dynamics. Students offer ideas about how they could use variations in their own behavior to discover patterns in the viral behavior. As the experimenting proceeds and hypotheses are refined, the students improve their ability to predict the viral outcome based on a certain set of (experimentally configured) behaviors. Through experimenting and collecting additional data about the relationship between their own behavior and the behavior of the virus (by conducting additional simulations), they are eventually able to state the rules that govern the viral behavior. This process is a form of scientific experimentation, in which a system is probed under various conditions to reveal the underlying processes that govern the system's behavior.

In Episode 2 the first example of experimental design was uttered. Rick proposed a method to figure out why some people didn't get sick when he exclaimed, "We should all meet each other." At that time, his proposal was ignored by most of his classmates, as there was no community agreement on what aspect of the problematic situation was under investigation. As their investigation moves forward, students' propositions for a variety of experiments to reveal the underlying dynamics of viral transmission become more frequent and focused.

Episode 4

Researcher: Do you have a strategy to avoid that [the virus]?

Allison: Stay away from people.

Student: But you don't know who.

Allison: That's what makes it confusing.

Rick: 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.

Doug: How 'bout all the people, each one [has a] partner, and then only meet with one person and whoever gets sick.

Rick: Everyone turn their badge around so no one can communicate with them and whoever's thing turns red first.

Doug: 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.

Stacy: 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.

And then we could record, like, who we shared with.

In this episode, a number of students describe possible experimental protocols. Rick wants everyone to avoid meeting other people in order to determine whose Tag shows viral symptoms ("lights up") first. He feels his plan will help determine the identity of Patient Zero (the initial host). Doug is concerned that Rick's plan does not control for the possibility that Patient Zero may just be a carrier and never display the symptoms of the virus. Stacy wants to run an unconstrained simulation and watch for the first appearance of viral symptoms. Over time, many students propose experiments, and the group decides which ones they want to conduct, often based on a comparison between the data the experiment is expected to produce and the currently available facts. Because there is a high level of iterativity and flexibility in Participatory Simulations, it is easy to accommodate as many experiments as the students want to run.

The students in the study exhibit a remarkable level of pride and ownership about their proposed experiments. All students possess the ability to articulate experiments, which, after all, are really prescriptions for altering their own behavior in a way that they feel will illuminate the rules of the virus. Any student can offer an experimental suggestion or direct the group to take a particular action and observe the results. It is up to the group to determine whose suggestion makes the most sense given the problem at hand.

Episode 5

Allison: I think we should just turn ours on and wait and see whoever gets sick first.

Rick: (Leaping out of his chair) THAT WAS MY PLAN!
You got that on tape right, I said it first!

… conducting the experiment…

Rick: We're supposed to chill.

Student: Allison you wanna exchange?

Allison: No, we're not supposed to have anybody.
Everybody's supposed to have zero.

Stacy: Is everybody supposed to have zero?

Researcher: That’s what I thought.
Rick: This is my experiment!
Tom: Oh, I get it. We’re trying to see if anybody turns up red.
Student: One minute.
Allison: I think we should give it ten minutes.

The students conceive the experiments and retain complete control over the experimental runs, though the facilitator can aid students during those runs. This student control is possible because of a unique attribute of Participatory Simulations—there is no simulation unless all of the student-agents create one. If any class member becomes marginalized, either because he is confused as to the nature of the experiment or because he is trying to subvert the experimental process, the group pulls him back in.[9] Re-running a simulation or conducting an experiment in this environment necessitates the participation of every student. Otherwise, it is as if the simulation is only partially running, and that situation yields unusable results.

Episode 6
Stacy: Oh look, it’s red.
Allison: Just only beep her once and that’s the only person you meet with is Stacy.
Rick: Why? Then we’re all gonna end up with it!
Allison: No, ‘cause we have to see who’s immune.
Doug: I’m not going to beep her.
Rick: I don’t want to beep her.
Allison: You have to or else the experiment won’t work.

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[9] See (Granott, 1998) for a discussion on defining the size of, and subsequently analyzing, the unit of collaboration.

In both Episodes 5 and 6 there is community negotiation about the design and execution of the experiment. Students continue to offer ideas for new experiments and ask for explanations about why certain propositions are expected to yield particular pieces of information from the simulation. But, once the group has begun to collect data, students exert pressure on one another to comply with the stated protocols. The nature of the Participatory Simulation ensures that all of the class members work together. In this way, Participatory Simulations differ from collaborative environments where the facilitator must keep all of the students together. As Allison explains to her classmate, Rick, “you have to [participate with us] or else the experiment won’t work.”

Conclusions

The students in this pilot study were first challenged to meet a lot of people without catching the virus and then encouraged to articulate a clear understanding of the simulation. The Participatory Simulation that enabled their activities was a motivating learning environment. Students worked together as they figured out what was happening in the simulation. As in a traditional microworld, the students needed to understand the underlying rules of the simulation in order to fully comprehend its dynamics and final outcome. They helped each other gather evidence, define the problem, and build theories about the dynamics of the system. Finally, they designed and executed experiments to test their hypotheses about the rules of their simulation environment. The students learned about these rules not by mastering a specific symbolic representation of them but by considering and modifying their own interpersonal interactions and observing the resulting viral dynamics until they could reliably predict an experimental outcome. For instance, at the end of the study, they could predict who would or would not get sick after meeting Patient Zero and how long it would take for an infected person to show symptoms of the virus.

During this study, the students played a total of six virus "games." Each simulation game took only a few minutes to play; however, students typically spent more time—up to 25 or 30 minutes—discussing each game and planning their strategy for the next one. In the first few games, students were not inquiring into a well-defined problem. Instead, their focus was on general observation and data collection. As they gained further experience in the simulation environment, they agreed on a few specific problems that they wanted to solve. In the later games, they were more systematic as they designed experiments and collected data to confirm or deny their hypotheses.

An analysis of the episodes from the first Participatory Simulation game reveals that instances of data collection and preliminary data analysis are more frequent than instances of experimental design. As the students tried to make sense of the first game, there was much discussion about each individual's experience in the simulation. There was almost no focus on designing experiments to elucidate the dynamics of the system. As a result of their lack of experimental planning, Game Two followed a very similar pattern of behavior and appeared to yield little new information about the dynamics of the system. In spite of this aimless appearance, Games One and Two were not unimportant. The evidence that the students gathered and the experiences that they accrued became the foundation for their more systematic approach to problem definition and experimental design in Game Three.

Game Three took place on the second day of participatory activities.[10] During this game, the students agreed on a problem: figuring out how the virus spread from student to student. Then, they worked together to analyze the data that they had collected. More focused experimental design emerged during this game. The concurrent pursuit of gathering new facts and designing and

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[10] Our experience in this and other Participatory Simulations has shown that allowing time for independent reflection results in more proficient problem definition and experimental design.

running new experiments continued through the next three games, increasing in the number of occurrences per game, until the group could articulate the underlying rules of the simulation.

This pattern of activity is consistent with the characteristics of scientific inquiry that we aimed to facilitate. As described by Hall (1996), "inquiry proceeds by a reflective interplay between selecting conditions in a situation that frame a problem and conceiving of related activities that will bring about a solution" (p. 211). In the Participatory Simulations environment, students framed multiple problems and executed experimental actions to discover the solutions to those problems. While this pilot study does not allow us to conclude that the Participatory Simulation alone caused students to engage in inquiry, it does allow us to observe that in this environment students are able to define a problem, inquire into its nature, and solve the problem. Our hope is that this experience will be one of many in which the students build and practice the skills of scientific inquiry.

Revealing the Rules

After four days of collaborative work and increasingly sophisticated experimental design, the students in this study articulated the underlying rules of the disease simulation,[11] namely:

- The virus is latent (invisible) for approximately three minutes,
- Patient Zero 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%,

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[11] Since the Tags are fully programmable, these rules can be modified or completely changed for a different Participatory Simulation. For example, some disease simulations consist of a virus and another opportunistic infection. Other simulations differ more substantially, like our pond ecology game in which participants model predator-prey interactions.

- 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.

Discussion

Many design decisions informed our construction of Participatory Simulations as well as their classroom implementation. Much work remains to be done to determine the best ways to use Participatory Simulations and other similar activities in the context of classroom learning goals. We hope that the following design principles will prove to be fruitful starting points as we continue to investigate the educational efficacy of Participatory Simulations.

Create a Compelling, Direct Experience

Participatory Simulations bring students into direct contact with scientific phenomena, by deploying the phenomena in the students' own interpersonal space. Because the simulation occurs in real space with students as agents, there is no gulf between participants' immediate experience and the simulation—they *are* the population that is being affected. Participants' internal conditions or responses to the simulation are not treated as separate from their inquiry into the simulation. Though the Participatory Simulation is an intentionally contrived environment, the students are compelled by their experience, often exclaiming during the virus simulation that they have "died" or "caught HIV."

Far from preventing inquiry or impeding the study of important scientific material, participants' personal experience in the simulation reduces the barrier to entry for the design and execution of scientific experiments. This reduced barrier may occur because Participatory Simulations ask the students to consider and explore patterns in their own behavior. Any participant can collect data (by reporting on their own experience or that of a peer) or propose an experiment (by suggesting a new pattern of human behavior). The virus simulation analyzed here supported a rich set of experiential and experimental outcomes in a socially meaningful context.

Facilitate Similar but Non-identical Experiences

The activities in a Participatory Simulation are designed so that every student has a similar and meaningful experience. Similar experiences of the activity ensure that the students share a common base, from which they explore the simulation. When a participant describes her experience of the activity, her classmates can understand and relate to her description, in part based on their own experiences. Later, when students collect data and propose experiments, they are all equally prepared to take part in these activities. Meaningful experiences ensure that every participant's experience is important with respect to understanding the behavior of the whole simulation. Because a Participatory Simulation is a completely distributed system, no single Tag is "running" the whole simulation. No one student's Tag is more or less important than any other student's Tag,[12] and similarly, no student's experience is any more or less important than any other student's experience. In fact, all of the students must contribute their experiences to the group discussion in order to make it possible to understand the dynamics of the system. Stated another way, each student's own vantage point must be articulated and explored in order for the group to

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[12] With the possible exception of Patient Zero who begins the infection; however, that designation is chosen randomly at the beginning of each game, meaning that (in this case) Patient Zero might be Doug the first game, Rick the second, and Liz the third, etc.

achieve an understanding of the whole system. The activities themselves enable a "social organization in which all individuals have an opportunity to contribute something" and "to which all feel a responsibility" (Dewey, 1988, pp. 34-35).

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 their descriptions build one by one, the students begin to develop an understanding of the system 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.

Participatory Simulations enable a kind of collaborative learning in which every child's experience builds towards an understanding of the whole. However, Participatory Simulations set up a different structure for collaboration than many other forms of collaborative learning do (Aronson, Blaney, Stephan, Sikes, & Snapp, 1978; Collins, Brown, & Newman, 1989; Slavin, 1996), because only a collaborative effort that engages all of the participants will enable the group to construct a model of the whole simulation. Every student needs to share his or her experience of the simulation and every student must participate in the experimental runs of the simulation. The process involved in building a collective understanding of the whole system 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.

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 Study this design choice accomplished two important goals. First, the Tags do not get in the way of the natural communication between students. Second, though the technology is quite unobtrusive, the students become deeply engaged in the disease experience.

There are many well-documented and varied examples of Computer-Supported Collaborative Learning (e.g., Koschmann, 1996). Participatory Simulations provide another example of a computer-based collaborative environment that fully supports 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 with each other and the simulation are not constrained by large monitors or awkward technology configurations.[13] Moreover, the minimal technology display seems to encourage students to use their own imagination and prior experience during the activities. The students are able to use social cues and knowledge about each other to enhance their engagement in the game. Picture Rick's pride when he exclaimed 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."

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[13] See (Stewart, Bederson, & Druin, 1999 and Stewart, Raybourn, Bederson, & Druin, 1998) for a different approach to enabling multiple students to interact with a single computer.

Or the notion that Doug started out with the virus because he was "dirty." On the last day of the project, two students recall their experiences:

Episode 7

Tony:	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.

Episode 8

Doug:	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.

The Participatory Simulation allows the inclusion of the prior knowledge, attitudes, habits, and interests that the students bring to the experience. The students who participate in Participatory Simulations draw on the framework of the simulation and their own knowledge and imagination as they experience in the simulation. They act and respond as though the simulation is real even though there is very little explicit visual support for the metaphor of the game.

The Tags' minimal display does not impair the students' ability or willingness to suspend their disbelief about the simulation, and the unobtrusive nature of the Tag technology supports rich interactions among a large group of students. This result 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.

Add Coherent, Consistent Rules to the Experiential World

For many years role-playing games have entertained children and adults. These games, like Dungeons and Dragons, enable participants to adopt certain personas, and in so doing require that the participants behave like their characters would in any given situation. Computers, and in particular the Internet, have expanded the range and popularity of these games (Turkle, 1995). The Thinking Tags create a new kind of role-playing game, which combines the immediacy of real-life adventure with the consistent rules of mediated games and microworlds. Without constraining the communication or the behavior of the students, the Tags provide a tremendous amount of structure in the environment. The Tags carry the underlying rules of the simulation (viral rules in this study) into the students' world. In some sense, the Tags transform the students into agents in a microworld, even as they allow the students to retain their own personalities.

Bringing a microworld into the realm of students' experience enables them to explore the underlying formal structure of that world without abandoning their own perspective. They make use of the consistent behavior of the Tags as they design experimental protocols to reveal the rules that govern viral behavior. Each of these components of the Participatory Simulation arises because the Tags create an environment that is initially mysterious but upon further reflection and action becomes transparent. The use of the Tags allows the students to reach transparency through a new path that draws upon the students' own personal experiences and their own systematic explanations of those experiences.

When designing this Participatory Simulation, we constructed a simulation that explores a few important concepts, rather than creating a simulation that closely mirrors a real life situation. In this example, we focus on the concepts of latency and immunity. Though many students compare this Participatory Simulation to HIV, we do not model any of the complexities of HIV transmission (and the infection rate of 100% is quite different from that of HIV). We purposely include the artifact of only being able to meet another person once in this simulation because it makes the model tractable, not because it increases fidelity to a real world disease. Roughgarden (1996) called this type of model, which seeks to capture the most fundamental parts of the system and illustrate a general principle, an “idea model.” Participatory Simulations allow us to create a rich learning environment that is based upon a “small cluster” of essential ideas (diSessa, 1986), in this case latency and immunity. It may be that more complex systems models are better explored through other media, including microworlds and traditional simulation environments.

Enable Students to Create their own Solutions

In the pilot Participatory Simulations Study, students were not given a specific vocabulary to use when discussing the rules of the simulation, nor were they given an alternative written representation to describe the data they collected or the hypotheses they proposed. This lack of pre-defined structure for meaning-making activities appears to be both promising and problematic.

Throughout the activities, but especially after the third game, the students endeavor to clearly express their ideas so that others can follow the points they are making. In time, they begin to agree on ways to talk about the activity that everyone can understand. Here, they use the Tag numbers to express the concept of immunity.

> Episode 9
>
> Tony: It was a pattern like that 20 21 thing. The numbers.
>
> Meredith: It was 1 2 11 21.

Tony: I <u>said</u> the 21 thing.

Meredith: It wasn't specific.

Tony: It was specific—you knew what I was talking about. It was specific enough.

When Tony mentions the "20 21 thing," he is referencing the fact that he thinks a certain set of Tags are immune to the virus. When Meredith corrects him by indicating *exactly* which Tags are immune, he protests, pointing out that even if his comment was not precise, it was sufficient for her to understand what he meant.

This type of discourse is consistent with that of many other Participatory Simulations we have run, in which participants digress from data collection or experimental design to settle on a precise meaning for "immunity" or "carrier." (In the case of immunity, students typically discuss whether or not immune people can infect others even if they never show symptoms of the virus. In the case of a carrier, participants usually debate whether or not a carrier can ever show symptoms of the disease.)

In its current implementation, facilitators of a simulation do not provide correct definitions for these or other debated terms, even if the definition that the students ultimately agree on is not precisely correct. This process allows the students to arrive at their own vocabulary for articulating the rules of the simulation. While we have not yet undertaken extensive research in this area, the consistency with which various student groups work to define specific meanings for their descriptions of the simulation suggests that more research into this activity may be warranted.

Similarly, the facilitator in this study did not suggest any kind of alternative representation for the data or the rules of the simulation. Some groups of students try to design charts, diagrams, or other graphical depictions to aid in their analyses of the problem. The group in this pilot study drew a chart on the board of the last person that each student had met (during Episode 3). Unfortunately, unlike creating representations for system-wide behaviors and outcomes, it is quite difficult to represent individual behaviors and outcomes in agent-based simulations (like this Participatory Simulation) in a manner that illuminates the key interactions (e.g., Feigenbaum, Kannan, Vardi, & Viswanathan, in press). Other researchers have explored the cognitive gains that people make when creating their own representations (Bamberger, 1998; diSessa, Hammer, Sherin, & Kolpakowski, 1991; Greeno & Hall, 1997; Hall, 1996; Nemirovsky, 1994), and we hope to find a way to include such activities in future Participatory Simulations.

In fact, during this pilot study, the researcher facilitated all of the Participatory Simulation activities. While this structure did enable us to explore the students' behavior and inquiry, it was not ideal for investigating the role of the facilitator. We expect that, as in problem-based learning, the facilitator's role in Participatory Simulations is complex and important to the educational success of the activity. A number of teachers, in high schools, universities, and graduate schools, have begun implementing Participatory Simulations in their classrooms. We anticipate learning more about the complex relationships that support this learning activity through an analysis of their classroom experiences.

This pilot study suggests that deploying microworlds in real space offers an opportunity to re-evaluate the role that structured experiences can play in understanding the mechanisms that govern patterns and processes in the world. We hope that future research will help shed light on the ways that participating in simulations can support children's developing scientific understanding.

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