Participatory Simulations: Envisioning the networked classroom as a way to support systems learning for all

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Abstract: The participatory simulations project brings together three lines of research—student understanding of complex dynamic systems , the use of participatory activities to augment student experience and the use of computer-based technologies to enable exploration of and reflection upon a domain of inquiry. These trio of goals can be significantly enabled and advanced through emerging network technologies. We argue that the study of dynamic systems stands as a *new form of literacy for all – enabling us to track and make sense of the evolution of systems across time*. Participatory Simulations Activities, on their own, are a powerful means for studying dynamic systems – and they can also support new forms of classroom interaction and can serve to prepare the way for engagement with computer-based systems modeling. To accomplish these goals, we introduce a new architecture, HubNet. HubNet is an open client-server architecture, which enables many users at the "Nodes" (typically handheld devices) to control the behavior of individual objects or agents and to view the aggregated results on a central computer known as the Hub. This network of nodes is integrated with a powerful suite of modeling, analysis and display tools that together give users the capacity to "fly' the system in intuitive mode, to reflect on the emergent result of their simulation and, also, to encode their strategies as rules which the system can then run independently. The HubNet system is in use in several middle and secondary classrooms. Two illustrative cases of classroom use are presented and analyzed.

Keywords: Simulations, modeling, emergence, mathematics education, science education, experiential education

Introduction

In this paper, we describe a new network-based architecture, HubNet, designed for enabling students to engage in participatory simulations of complex dynamic systems. Working together with a commercial partner, we are engaged in an iterative design and test cycle to refine the HubNet system and its associated activities. Early

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versions of HubNet are in use in classrooms in Boston Massachusetts and Austin Texas. This work is being undertaken under the auspices of the Participatory Simulations Project (PSP) – an NSF-funded collaboration between Northwestern University's Center for Connected Learning[2] and The University of Texas at Austin.

In the following sections of this paper, we introduce our project and illustrate two cases of its use in school settings. We begin with a brief history of the use of participatory simulations in math/science education, move on to describe the HubNet architecture and its design rationale. We then present the pedagogical principles and practice that govern our use of HubNet in classrooms. In the body of the paper, we present and analyze two classroom scenarios using HubNet. The first of these, the "Gridlock" activity recruits class members to control traffic lights in a city traffic grid. The collaborative goal of the activity is to optimize traffic flow. In the second activity, PeopleMolecules, students play the role of individual gas molecules in a chamber. Students' goal in this activity is to pay close attention to the relationship between their own individual speed, as they move in the "chamber", and the distribution of speeds in the class collective. We conclude by summarizing the cognitive and social affordances of the HubNet technology and then outline future directions for technology development, activity design and cognitive research.

What's a Participatory Simulation?

Students engaged in a participatory simulation act out the roles of individual elements of a system and then observe how the behavior of the system as a whole can emerge from these individual behaviors. The emergent behavior of the system and its relation to individual participant actions and strategies can then become the object of collective discussion and analysis.

While such participatory role-playing activities have been commonly used in social studies classrooms, they have been infrequently used in science and mathematics classrooms. Our use of the term participatory simulations is intended to refer to such role-playing activities aimed at exploring how complex dynamic systems evolve over time. Our focus is primarily on learning in science and mathematics classrooms For example, each class member could play the role of a predator or prey in an ecology and engage in a classwide discussion of the resultant global population dynamics. A wide ranging set of sample content areas for participatory simulations include the spread of a disease, the flow of traffic in a grid, the distribution of goods in an inventory system, the diffusion of molecules through a membrane, or the emergence of an algebraic function from a set of points (Wilensky & Stroup, 1999a).

Why do Participatory Simulations and Emergent Activities Matter?

A core commitment of the PSP is to research the use of participatory simulations as a way into systems dynamics and complexity learning for *ALL* students. During recent decades, there has been a recognition of the importance of understanding the behavior of dynamic systems—how systems of many interacting elements change and evolve over time and how global phenomena can arise from local interactions of these elements. New research projects on chaos, self-organization, adaptive systems, nonlinear dynamics, and artificial life are all part of this growing interest in systems dynamics. The interest has spread from the scientific community to popular culture, with the publication of general-interest books about research into dynamic systems (Gleick, 1987; Kauffman, 1995; Kelly, 1994; Holland, 1995; Waldrop, 1992).

It is the stance of the PSP that the study of dynamic systems is not just a new research tool or new area of study for scientists. Our stance is that the study of dynamic systems stands as a *new form of literacy for all*, a new way of describing, viewing, and symbolizing phenomena in the world. The language of the present mathematics and science curriculum employs *static* representations. Yet, our world is, of course, constantly changing. This disjunct between the world of dynamic experience and the world of static school representations stands as one source of student alienation from the current curriculum (Chen & Stroup 1994; Wilensky & Reisman, 1998). By enabling the study of dynamics, we empower students to gain powerful access to understanding phenomena as diverse as weather dynamics, evolution and origin of life, food web ecologies, or kinetic molecular reactions.

Research in mathematics/science education and cognitive science (Chi et al, in press; Jacobson & Angulo, 1998; Mandinach & Cline, 1994; Resnick, 1994; Wilensky & Resnick, 1999) has documented that students have considerable difficulties in making sense of complex systems. In particular, Resnick and Wilensky have documented

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[2] This work began at the Center for Connected Learning and Computer-based Modeling (CCL) at Tufts University and migrated to Northwestern with the CCL.

the considerable difficulties people have in making sense of emergent phenomena, global patterns that arise from distributed interactions, central to the study of complex systems. This constellation of difficulties in understanding emergent phenomena and constructing distributed explanations of such phenomena has been labeled the "deterministic/centralized mindset" (Resnick & Wilensky, 1993; Wilensky & Resnick, 1999; Resnick, 1996). Our aim in the PSP and in developing the HubNet system is to be catalytic in helping secondary and post-secondary students move beyond the deterministic/centralized mindset and advance their understanding of how systems unfold and develop over time.systems. We view the facility with systems thinking, modeling and emergence as a new and necessary form of literacy for our citizenry.

The theoretical and computer-based tools arising out of the study of dynamic systems can describe and display the *changing* phenomena of science and the everyday world. A core conjecture of the PSP is that the affordances of participatory simulations, as supported by networked modeling and analyses tools discussed below, provide a powerful way into systems related sense-making that can help realize the vision of systems learning for all students.

What's New in the Participatory Simulations Project?

The list of what is new about the PSP includes the development and use of innovative networked classroom-based technologies to connect learners' evolving intuitions with powerful modeling and analysis tools and the pursuit of fundamental research into learning about systems through the use of network-based interactivity.

By interconnecting the artifacts created from learner activity with powerful modeling and analysis tools the enactive aspects of participatory simulations stand to be deepened and extended. Additionally, learners working in the networked environment make overt and visible their strategies in relation to generating different kinds of emergent behavior. In so doing, these strategies become increasingly well-articulated and refined in ways that scaffold both learner understanding of dynamic systems and the actual use by learners of the tools themselves. Through the participation in and analysis of emergent activities, we expect learners to come to see the tools as increasingly useful in helping them to further articulate their insights into the emergent behavior of dynamic systems. These tools enable them to analytically understand these systems, in effect working with the mathematics of change without needing to master the formalisms of differential equations. For researchers, the network-based activity enables save and replay, making visible learners' ideas and ways of organizing their experiences, which should significantly advance our understanding of these forms of emergent learning.

A Brief History of Participatory Simulations

The first major instance of which we are aware where a participatory simulation was used in the context of systems dynamics and systems learning was *The Beer Game* as developed by Jay Forrester and his systems dynamics group at MIT in the early 1960's. There is a significant literature related to The Beer Game and interest in this participatory simulation has been recently revitalized as a result of its appearance in Senge's widely read *The Fifth Discipline* (1990). The game does much to highlight the ways in which costly unintended behaviors of a system (in this case beer inventory in a distribution system) can emerge from participants attempting to act rationally in their localized role (e.g., as beer retailer, wholesaler, distributor, or producer). A number of other such PSA were developed at this time. One popular PSA, FishBanks (Meadows, 1986) was developed by Meadows as an "interactive, role-playing simulation in which groups are asked to manage a fishing company." Students try to maximize their assets in a world with renewable natural resources and economic competition.

More recently, new classes of so-called "object-based" simulation activities have been developed (Resnick & Wilensky, 1993; 1998; Wilensky & Resnick, 1995). In these so-called "StarPeople" activities, participants typically play the role of "ants" in an anthill simulation, moving around the room and exchanging "messages." After participating in these StarPeople activities students observe the emergence of global patterns from their local interactions. These pattern become the objects of reflection and discussion.

Participatory Simulations Activities and Computational Tools

Throughout much of the fifty-year history of participatory simulations computational technologies have played a central role. The systems dynamics group at MIT developed a class of computational "flight simulators" to be used by individuals and groups of managers to gain experience flying a complex dynamic system like a modern business. More recently, multi-player networked versions of the beer game have been implemented (Coakley et al, 1995) and it is now even possible to immerse oneself in a multi-player versions of the game on the internet (Powersim

Corporation, 1998). A multi-player calculator-based version of the beer game participatory simulation also has been implemented and used with both school-aged and adult learners (Wilensky & Stroup, 1998, 1999; Wilensky, 2001a). Management trainers have argued that there is a need for a tighter coupling between computer simulations and user experience. In possibly the first known use of the term participatory simulations, Diehl (1990) constructed systems that gave users more control over and participation within the simulations by allowing users to input more real word decisions and view output of familiar reports. These simulations were modeled using finite-difference tools like STELLA (Richmond & Peterson, 1990).

In contrast to the "aggregate" finite-difference computer modeling tools used to analyze simulations like The Beer Game, these simulation activities have been designed to be further explored using object-based parallel computer modeling languages (OBPML) (aka multi-agent modeling languages) such as StarLogo and StarLogoT (Resnick, 1994; Wilensky, 1995; 1997b). Borovoy, Colella and fellow researchers at MIT (Colella et al, 1998; Borovoy et al , 1996; 1998) have developed wearable computational badges (or "thinking tags") that allow users to move freely while communicating information between badges. Colella (1998) developed, implemented and researched student learning with one of the first instances of a participatory simulation supported by a thin layer of computing technology. Disease propagation models are natural candidates for this kind of participatory simulation and have been implemented by a number of researchers and curriculum developers (Colella et al, 1998; Stor & Briggs, 1998).

A significant innovation in this project is a commitment to exploring the complementarity of these two fundamental kinds of dynamical systems modeling – aggregate and object-based approaches. This compels a careful attention to a) the relationships between macro- and micro-levels of understanding a system (Chen & Stroup, 1994; Wilensky, 1993; 1997a); b) thinking in levels (Wilensky and Resnick, 1999); c) systems thinking (Roberts, 1978; Mandinach & Cline, 1994; and d) the analysis of systems like gases (Wilensky, 1993; Wilensky, 1999; Wilensky, Hazzard, and Froemke, 1999). Through the use of participatory simulations and attention to the kinds of constructs learners articulate and extend in relation to both the aggregate and object-based modeling environment, we expect to gain deeper insights into how these kinds of distinct but inter-related forms of analyses interact and complete one another.

What is HubNet?

HubNet is the name we have given to a networked architecture we have designed to give students the experience of participating as elements in a simulation of a complex dynamic system. HubNet is an open client-server architecture, which enables many users at the "Nodes" to control the behavior of individual objects or agents and to view the aggregated results on a central computer known as the "Hub". This network of nodes is integrated with a powerful suite of modeling, analysis and display tools that, together, give the capacity to "fly" the system in intuitive mode, to reflect on the emergent result of the simulation and to encode student strategies as rules which the system can then run independently.

Figure 1. Students engaged in participatory simulation supported by HubNet calculator network. On the left each student sees her/his own calculator view. On the right is the projectedclassroom display of the emergent result.

The HubNet architecture was developed in stages. Much of the research reported on herein employed a workable subset of full HubNet functionality. Substantially more of the full design is implemented at the time of this writing. The present HubNet system consists of 1) a network of graphing calculators called TI-Navigator developed in concert with our commercial partner, Texas Instruments. 2) a server, which talks to the TI-Navigator network and 3) an object-based parallel (aka multi-agent) modeling language, NetLogo (Wilensky, 2001b), which is a substantial enhancement and extension to the StarLogoT (Wilensky, 1997) language. NetLogo enables users to build object-based models of systems consisting of thousands of distributed elements. 4) A shared public display space such as a computer projection system that enables participants to observe the evolution of their simulation. We call this four-component HubNet sub-system ClassLogo. We are currently extending HubNet to integrate aggregate modeling languages, such as STELLA and Model-It, extending the dialogue between object-based and aggregate approaches.

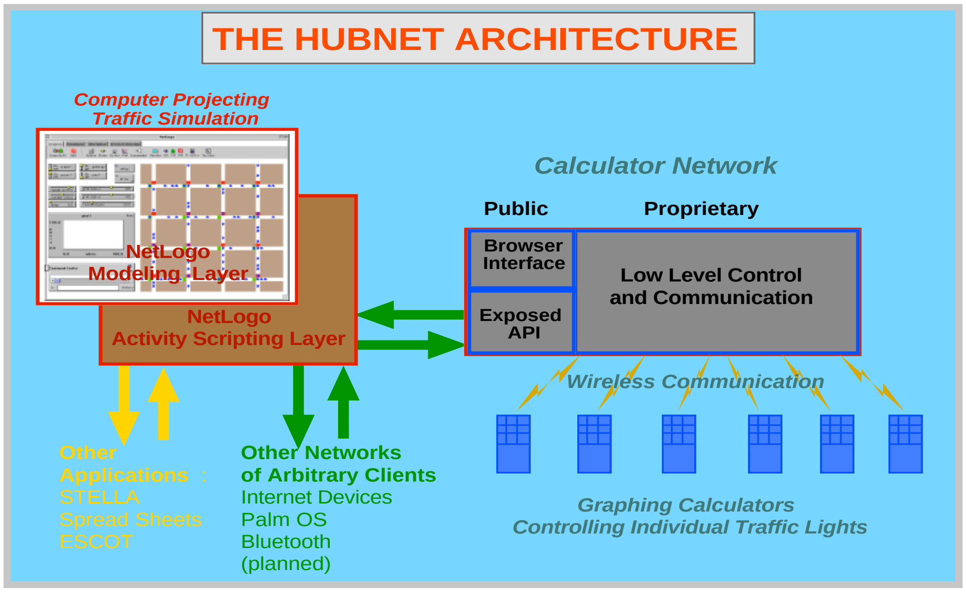

Figure 1. The HubNet architecture.

Many more analysis and display tools will also be integrated, as well as ‘hooks’ allowing a much wider array of node hardware including arbitrary Internet hosts. In the some of the research reported on herein, an early wired version of the TI-Navigator network was used. Current versions of TI-Navigator run wireless.

HubNet Design

A potential barrier to wide-spread adoption of networked activities is the difficulties in authoring new PSA. Our Java-based development effort of NetLogo extends the object-based modeling capabilities of StarLogoT by having the NetLogo language also serve as an authoring language for the creation of HubNet-based participatory simulations. Just as object-based models are extensible (Wilensky, 1997a, 1999), the network-based emergent activities created in NetLogo are extensible. Under the HubNet design, the parallelism of StarLogoT and NetLogo as modeling environments is being significantly extended to also serve as a way of coordinating and authoring activities for a space of networked computing devices (nodes).

The HubNet architecture is designed to be open to a wide variety of node clients including many handheld devices as well as internet hosts. For a number of design reasons, we have focused our work so far using TI graphing calculators as the nodes. A significant reason for this choice is the substantial presence of such calculators in secondary school mathematics and science classrooms. There is a large user base of students and teachers. The density of such calculators in classrooms allows for easier adoption as the incremental hardware costs are manageable (each classroom need only need only acquire one internet-enabled computer and the Navigator network box). Other reasons for this choice include the robustness of the devices themselves (they pass the “drop test”), the low maintenance costs, the significant resident functionality and the large training and support network available for teacher professional development (e.g., T-cubed[3]).

The calculator can also interact with real world devices such as sensors and motors, CBLs (calculator-based laboratories) and CBRs (calculator-based rangers), allowing for a wide range of participatory simulation activities to be implemented in the classroom. Additionally, calculators can upload and download data sets, upload and download programs (e.g., applets), monitor key-presses at the hand-held level, support real-time interaction as in network computer games, and form collaborative groups of various sizes (e.g., peer to peer, small groups, and whole class modes).

These reasons for using the proprietary TI Navigator network are compelling for current classroom use. But, the HubNet architecture itself is general and can work with any network of nodes. We anticipate using personal digital assistant (PDA) devices such as Palm Pilots, WinCE devices, wireless phones and, of course, internet-enabled computers with the HubNet system. HubNet supports fully networked modes of interaction with and among learners. While *synchronization* between the data on the handhelds and the Hub is supported in this model, the model can also support on-going, *real-time interactivity* and exchange (Figure 1).

In the ensuing sections of this paper, we describe two HubNet activities in detail. One of these, the Gridlock activity, involves students interacting with the network in real-time. In this activity, students assume control of stoplights in a city traffic grid. Simulated cars move through the grid and by pressing a key on a handheld, the color of a light changes in real time. Students work to create the best traffic flow they can. The second activity, the PeopleMolecules simulation is an example of synchronized interactivity. In PeopleMolecules, students play out the role of individual gas molecules in a chamber. Each “molecule” has a motion detector attached to it, which captures its speed as it moves about the chamber. This data can then be analyzed locally on the handhelds or uploaded – synchronized with the HubNet system for replay and analysis. These activities will be discussed in detail in subsequent sections of this paper.

A design goal of the HubNet network is to support a range of different topologies for collaboration among learners including person-to-person, small group and whole class interaction. This inclusive range of interactivity and richly textured forms of collaboration is vital for supporting the widest possible range of participatory simulation activities.

Activity Design

We believe that participatory activities using HubNet can effectively support a wide range of learning, and that, in the long run, a technology like HubNet that supports this level of interactivity will be widely adopted in classrooms. To help in our efforts to understand and support this evolution in classroom practice, our activity development has come to be structured by a set of general design principles.

1) We endeavor to strike a balance between two competing curricular agendas: the desire to help students understand important aspects of the traditional curriculum and the desire to support the introduction of fundamentally new systems ideas like emergence, feedback, and self-organization into the curriculum. Rather than develop activities that are narrowly of one kind or the other, we look to instantiate this balance in each activity. At a practical level, this means that for activities that are more transparently linked to the traditional curriculum, we try to draw out significant connections to system ideas. For activities that are more deliberately about dynamic systems, we highlight connections to important ideas in traditional curricula.

2) In the PSP, we are targeting areas of the curriculum that are currently identified as “hard” for students to learn. It is these potential “high gain” target areas that do the most to illustrate the long range potential of HubNet supported participatory design.

3) We look to develop activities that enable learners to connect their personal experience to the content to be learned. Primarily, we do this by authoring activities that actually give new experience to thew students, a kind of experience not usually available to them in their daily life -- the experience of seeing the connection between their individual (micro- level) behavior and a classwide pattern (at a macro- level). We also look for opportunities to

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[3] Texas Instruments’ Teacher Network is called ‘Teachers teaching with Technology’, or ‘T-cubed’.

leverage personal experience gained outside of the classroom (such as knowledge gained in navigating the world) in order to enable learners to more easily enter into a participatory simulation activity.

4) We look to develop activities that are generative. Generative activities are what we describe as "space creating" activities (Stroup, 1997; 1998). By "space-creating" we mean we try and develop opportunities for students to explore or create a space of possible responses to the activity and then to make sense of patterns that structure that space. This approach stands in sharp contrast to typical science classroom activity that seeks to collapse the space of student response to a single highly constrained response or behavior (e.g. a point in an activity space). There are, for example, lots of ways of controlling traffic in a traffic grid. Rather than immediately collapsing this multiplicity to a single "right" approach that is leading the students to "discover" the "optimal" solution, we want students to generate a space of ways of controlling traffic.

We aim to develop activities that highlight the process of modeling and the power of embodied sense-making. This does not, necessarily, mean that our simulations are exact replicas of the systems they represent. The simulations model some aspect(s) of the systems they are about. They are like the systems in some way(s). But as is true for models and simulations developed at the frontiers of science, the models that often teach us the most are the models that differ in important ways from other models we know or even from the underlying reality they render. Good insights are often found in these gaps and it is the leveraging of these gaps that is at the heart of the activity of good modeling and scientific inquiry. To have learners make the most sense of the current models that are the stuff of scientific theory and to have learners make the most sense of the activities associated with doing science, contrasts are as important as convergences. In the people-molecules example discussed later in the paper, it is not that students moving about with motion detectors behave exactly like the molecules of a gas but rather that there are some aspects of simulating molecules in this way that will help students construct an understanding of kinetic molecular theory and how it is that one might come to believe that such a theory might be developed. We have found that, for the purpose of making sense of classical concepts such as the Maxwell-Boltzman distribution of gas molecule speeds, the contrasts between the distributions of speeds of the students in "people-molecules" and the classical distribution are as useful as the similarities.

Pedagogy Design

From a pedagogical point of view, participatory simulations make good use of the social space of the classroom (or other group setting). Each student is actively involved in the simulation – taking advantage of the parallel architecture of the network. Moreover, beyond the individual students, the class as a whole is engaged in the activity through observing, modifying and discussing the publicly shared projected space. The HubNet architecture together with the PSP activities afford putting what learners create at the center of developing understandings in this social space. We extend existing approaches to learning in a social space (e.g., Abrahamson et al, 2000) by being attentive to the shape and flow of discourse in the classroom and to the ways in which individual voices interact with and co-evolve with levels of group discourse. At the same time we are attentive to the ways that such collaborative technologies can transform traditional construction of understanding in a social space by creating new forms of inter-action. New forms of computationally-mediated gestures, like turning on or off a traffic light, are supported by the system. Similarly, new kinds of computationally-rendered artifacts, like graphs of traffic flow, are generated. We have developed an iterative pedagogical design that supports both extending and transforming traditional forms of individual voice/group discourse interactivity. At the center of this design is making thoughts and ideas visible in real-time for both the teacher and the students.

The first step in our iterative pedagogical design is making the goal of the activity clear. For the Gridlock activity the goal is to prepare a report for the Mayor of the City of Gridlock on how to improve traffic flow in the city. For the people-molecules activity the goal is to begin to understand important dynamic aspects of gases, including the distribution of speeds, by "becoming" gas molecules.

Next we have found it very important both as a way of catalyzing the processes of exchanging ideas and as a tool of ongoing assessment that we ask students to tell us what they know about the central element of a given simulation. For the traffic simulation this means asking students to brainstorm the kinds of things that they know impact traffic. For the people-molecules simulation we ask them what they know about the air in the classroom. Typically we have whole chalkboards full of ideas the students generate. At the same time we also gain top level insight into their thinking. We can then contrast features of what they know initially with the kinds of understandings that develop from participating in the simulations. We are particularly interested in the ways in which students understandings of systems shift from an early attention to relatively static features of a particular context to the dynamics and structural aspects of the system. With the Gridlock simulation students often begin by listing things like “potholes” and “time of day” as affecting traffic. With the people-molecules simulation they begin by listing features like “transparent” or even “weightless” to describe air. These ideas are important starting places for the exchange of ideas and they are important because they highlight the ways in which their previous learning has highlighted fixed surface features of their environment and not the dynamic interaction and structure of these systems (e.g. how volume of traffic associated with particular times of day creates patterns of traffic flow or how the dynamics of gas molecules create a stable “weightless” experience of air).

We then run the simulation. The first time through we begin by having students explore the kinds of actions and gestures they can make in the simulation before actually capturing the data from the simulation. For the Gridlock simulation we often have them become familiar with turning on and off lights before we put cars in the simulation. For people-molecules we have them practice moving around in an enclose space before turning on the motion detectors. We also draw attention to the interpretive features of the simulation like how the color of the cars might change as an indication of their speeds or how a particular graph is coordinated with aspects of the simulation itself. These interpretive features often require a round or two of running the simulation. Only then do we run the actual simulation – that is students engage in the participatory activity with instructions to pay attention to a particular aspect of the simulation. For Gridlock this means encouraging students to think about ways of improving traffic flow. For people-molecules this means they being attentive to how their individual molecule behavior interacts with the behavior of the “gas” as a whole.

Next is a reflective stage where students articulate what they have observed. Examples of these observations for the gridlock simulation and the people-molecules simulations are discussed later in the paper. A range of artifacts are appealed to in these reflections from the visible display of the number of cars at a traffic light to specific feature of a histogram for a given “molecule”. In addition to co-evolving strategies or understanding of the system learners at this stage will articulate conjectures about how the system works and possibilities for repeating the simulations. The use of various built-in analysis features of the calculator (e.g. histograms of one’s own movement), using analysis features of NetLogo (e.g. replaying the data from the “molecules” with the data from each molecule being associated with the motion of a particular agent in a NetLogo display), or using other analysis tools like spreadsheets to compute tables of difference. At this reflective stage learners often will begin to critique the model itself in terms of ways of making the simulation better. Because the simulations are extensible, changes can be made on the fly or – more typically – in preparation for a subsequent day. Sometimes the model might not actually have to be changed but the act of trying to clearly articulate how the behavior of the model would have to be different is itself a very powerful sense-making activity. The discourse of the classroom and the ways individual students give voice to their ideas become richer.

A next step is to run the simulation again in a way that is a refinement of earlier efforts. This refinement can be in pursuit of a particular way of replaying the simulation or a set of cases to explore (e.g. scaling some of the distinct strategies identified by learners). It is also possible to move to running models that are not participatory but with insights that come from the participatory simulations. Running people molecules can scaffold the engagement with various agent-based models of gases (e.g, GasLab, Wilensky, 1999; Wilensky et al, 2000).

The steps of this pedagogical design can then be repeated. With each iteration the texture of interaction become more nuanced. Student descriptions shift to be more dynamic and structural.

HubNet in the Classroom – Illustrative Examples

Most of our work in classrooms has been in middle school and high school science and mathematics classes. Typically we have worked in low SES settings. We are also committed to working with low “track” classes. Class sizes have varied from a low of eight students to a high of twenty six. In nearly every case the teachers have had very limited familiarity with technology and so these activities are quite new in many ways. It is also the case that participatory simulations create special challenges for teachers in terms of how to make best use of student-generated ideas. In discussing the kinds of learning occurring in relation to the two examples discussed below, we will also highlight some of the challenges for teachers. A significant focus for the recent activity of the project has been on supporting teacher learning in relation to running participatory simulations in their classes. Each simulation discussed below centers on a scenario that is meaningful to students and for which the class as whole has a goal to accomplish. By playing a role in the simulation, the knowledge students develop is more situated and embodied than it would be from just being presented with the scenario alone. Students are not simply "active" in a participatory simulation, they are *enactive*[4] and this stands to improve both student motivation and understanding. Student engagement and sense of ownership is further extended by the fact the students analyze the results they helped to create and can iteratively replay their actions and revisit the scenarios with what-if questions that can be explored.

Gridlock

Students are introduced to the Gridlock activity with the following scenario:

> *The mayor of the City of Gridlock is unhappy with the traffic situation in town. She has commissioned our class to improve the traffic situation in the city."*

Consistent with the pedagogical design outlined above, this scenario makes it clear that the goal of the activity is for the students to find ways of optimizing traffic flow for the city. We have run the Gridlock activity in a variety of settings, from middle school science classrooms, to secondary social science classrooms, undergraduate and graduate education classes, and at research conferences. The responses of students reported below come from two instances of running this activity in schools. One instance is a seventh-grade classroom from a school with a relatively low income student population located near Austin, Texas. Twenty-four students are in this ethnically and racially diverse classroom. The second classroom is from a moderate to high income, ethnically diverse school near Boston, Massachusetts. In the second school, students had significant access to computers for individual use. The use of the Gridlock participatory simulation occurred towards the end of a one month long, special unit on complexity, parallel processes and emergent phenomena. As part of this special unit, students explored and constructed models of complex systems using the multi-agent modeling language StarLogoT (a precursor to NetLogo, see description above). For the school in Texas such resources were not available, and so the discussions and analysis depended on the then-current capabilities of the HubNet system.

After the goal of the activity was introduced students were next asked what they know about traffic flow. The following exchange was from the Austin-area school:

T: What are some of the things that you guys listed that would be indications that traffic would be good or bad to you?

S: Accidents (laughter)
T: (While writing accidents on the board) Oh great, now we're going to do my spelling … Okay, raise your hand if I spell a word wrong.
S2: Not enough lanes.
S3: Speed bumps.
T: Yah there are some speed bumps …
S4: Autos
S5: Pedestrians
T: (laughs) "obstacles".

The listing continues until two chalkboards are filled with responses including:

Construction
Speed limit too high (causing more accidents)
Special lanes for trucks
Red lights too long
HOV [high-occupancy vehicle] lanes
Barrier walls too close for cars
Not as many intersections
The longer the light
Special events
Getting bored
Crashes
Lots of cars
Foot traffic
Cell phone drivers
Distracted drivers
Storms/road conditions

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[4] Enactive in a sense that is like the Aristotelian use of *memesis* – that is, enacting, representing or playing a dramatic role within a structured situation (Halliwell, 1987).

Roadwork
Dangerous drivers
Slow drivers
Fast drivers
Drunk drivers
Wider lanes
Debris in road (trees, trash, etc.)
Stop signs
Buses
Animals
18-wheelers

The sense is that learners can articulate a wide range of factors that can impact complex phenomena like traffic. Some of these responses are behaviors of individual drivers and others are related to the structure of the roadways or context for the behavior (e.g., HOV lanes, lights too long, etc.). Taken collectively, this list suggests that learners do have an initial appreciation of how agent behavior in a context or environment can have consequences for the emergent features of a complex system. For traffic this insight comes from their first person experience. Part of the purpose of participatory simulations is to leverage the learners' first person perspective in a way that can lead to more robust, incisive and powerful understandings of complex phenomena.

The teacher in both settings ran the NetLogo traffic simulation and projected the computer screen in front of the class. At first, students were not logged into the TI-Navigator network. The projected simulation starts running with cars driving east and north through the city. The city starts off with no traffic lights (Figure 2).

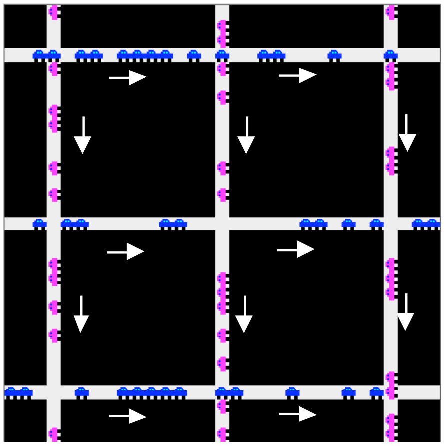

Figure 2. Traffic flow with no lights.

The traffic moves in two directions, left to right or up to down. A graph depicting the number of stopped cars also dynamically updates.

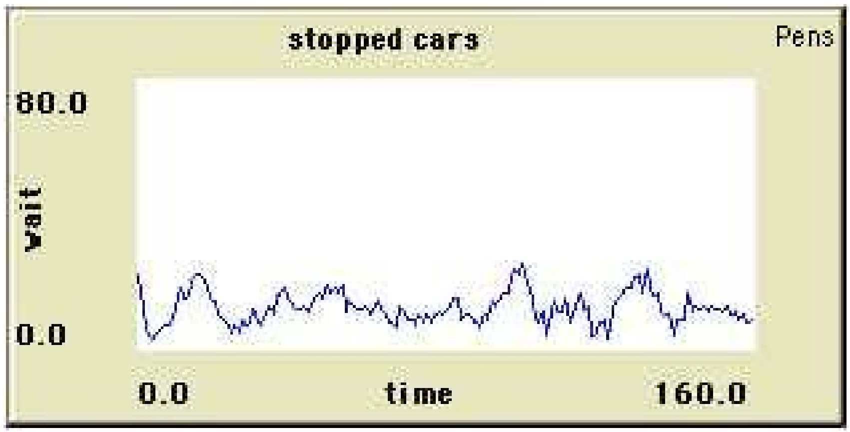

Figure 3. Traffic flow with no lights.

On first impressions, it looks like everything is running smoothly for this city. The average number of stopped cars is close to zero and this low number is confirmed visually by cars appearing to stop only occasionally. The problem is that the initial run of the simulation doesn't keep track of when cars are occupying the same location on the grid.

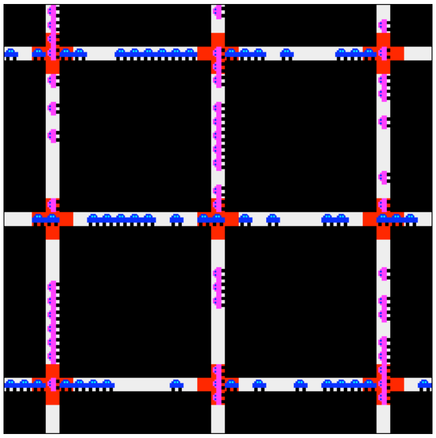

Figure 4. Accidents quickly result.

In real life, two (or more) cars trying to occupy the same location is called a crash. If the upfront simulation now shows these crashes – denoted with red crosses – every intersection quickly has a red cross on it (Figure 4). Traffic comes to a complete standstill. The initial introduction of the participatory simulation is continued by adding a single traffic light. When the simulation is run again, the teacher can turn the lights at the intersection green and red using a switch on the NetLogo interface (green in one direction means red in the other). It soon becomes apparent that accidents re-emerge at every intersection except for the one with the traffic light. Then additional lights are added and the accidents cease at those intersections as well. The issue then becomes, how should the grid be controlled?

Pedagogically the next step is to run the participatory simulation. In both classrooms students were asked to first arrange groups of desks in a grid matching the grid pattern of the projected computer grid. As can be seen in the following transcription from the Boston-area school, students start off exploring features of the simulation. Initially the lights are controlled manually for each of the intersections in the grid.

One light doesn't change and cars pile up behind it.
Students laugh.

Student 1: Eve[5] change your light
A chorus of students: Eve!
Student 2 (Eve): I'm trying, but it's not changing.
Student 1: It takes a little while.
Student 2: There, it changed. Why is it so slow?
Student 1: It takes a while to respond.
Teacher: In real traffic, it takes a while too. Human reaction times aren't immediate.

Students get very animated and are abuzz with excitement in trying to control traffic.

Student 3 (David): Eve, you have to pay more attention. Don't just look at your light, watch the light near you.
Researcher 1: So…, what is your name sir?
Student 3: David
Researcher 1: So, there was an interesting idea: Ilya says instead of watching just your own light, you could try to watch the lights near you.
Student 3: If the light behind you just changed, then you should change yours.

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[5] All names have been changed.

Student 4: Or maybe if you see a pack of cars coming, just change automatically? Couldn't we write that? [meaning the program code] We could count the number of cars behind each light. Couldn't we use 'who-max-of-patches' to find out which light has to change?
Researcher 1: you could write a reporter[6] that would return that for you..
Teacher: Yes, this model isn't that much harder to write than the regular models we have been doing. The language to write this is very similar to StarLogoT, it's called NetLogo and
Student 4: Couldn't we try to make all the lights red and just have one green?
Student 3: I'm trying to write the rules

Meanwhile, traffic accumulates at David's light.

Student 4: David, you're losing it. Push a button, push a button.
Researcher 1: you're getting pretty good at this real time task. Let's make it a bit harder.
Student 5: increase the number of cars?
Teacher: I'll increase the number of cars.

Frantic light changing ensues, but despite their best efforts, the city is gridlocked (all the cars are stopped).

Student 6: It's stopped!
Teacher: This happens in real cities too.
Student 7: It's just because we're slow to press the buttons.
Teacher: But real cars don't start and stop on a dime either.

Students make spontaneous connections to other areas of their knowledge and to generate strategies for controlling the traffic. Very subtle questions about logic, timing, phase and synchronization are engaged as students struggle both to create ways of talking about the traffic that are meaningful and to implement strategies making use of this language.

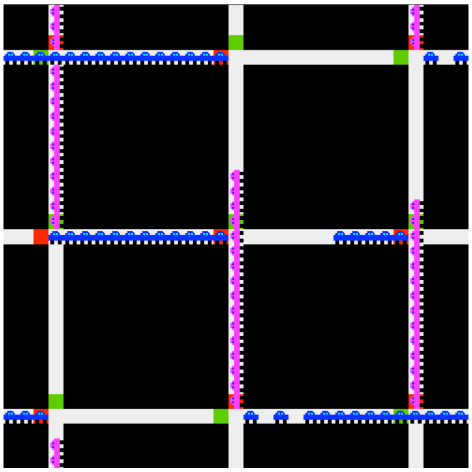

Figure 5. Uncoordinated Traffic

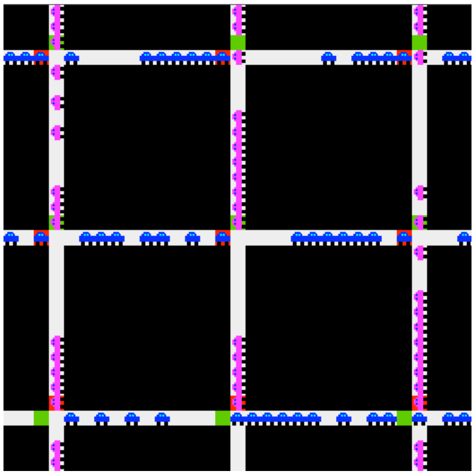

Figure 6. Lights synchronized

One of the spontaneous strategies is to synchronize the lights with a phase shift. Uncoordinated traffic is shown in Figure 6. In Figure 5, the lights in the top row turned green in the same direction together, then the lights in the second row wait a few seconds (phase shift) and turn green. This pattern cascades downward as traffic flow in that direction is synchronized. We had seen this coordination issue arise before and had implement the ability for students to set individual phase delays for their respective lights.

Picking up the Boston exchange again, the students have now reached a reflective stage in the pedagogical sequence. They begin to articulate a need for this kind of "phase" coordination of the lights. Initially the students articulate

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manual strategies for implementing a delay between the lights. They are then introduced to this feature in the participatory simulation and then proceed to use it. The pedagogy is iterative: implement a strategy, reflect on the results, articulate a modified strategy and then run the participatory simulation again.

Student 5: May I say something?
Teacher: Sure.
Student 5: I learned in social studies that England has an amazing system of locks and barges. It was about 100-150 years ago that they centralized control of these canals so that individual land owners would no longer be able to charge tolls in order to get through because if you took one route you'd be stuck at the discretion of the landholder. And they centralized, instead of doing, like we're doing now , have 12 individual people or controls over the canal system, they made it so that there would be one overarching set of rules because a model like this creates too much screaming and too much pressure.

The need to coordinate strategies becomes clear for the learners.

Student 7: So, let's see if we can coordinate the lights.
Student 4: But, this way is fun.
Student 5: It's fun for them [the light controllers] but it's not fun for the people in the barges.
Researcher 1; (joking). It's beyond the decentralized mindset.
Student 5: yeah, people are not ants.
Teacher: There is an auto mode.
Student 8: We could change the lights every 20 seconds
Student 2: Or some could change every 30.
Student 9: This is so cool!
Student 3: Yeah.
….
Researcher 1: We have an auto mode that makes it easier to coordinate the lights [in this way]. Let me set it up in auto mode.

Researcher 2 explains how to get into auto mode and segues into a discussion amongst students of what does the "phase" quantity. The feature is connected with a felt need expressed by the students.

Researcher 2: Now what does phase mean?
Student 8: It's like the number of seconds maybe?
Student 10: Or the number of cars that pass before the light would switch?
Student 8: The number of beats….
Researcher 1: It's now in auto mode.
Researcher 2: So there's a clock that goes 1 – 100 and whatever number you enter controls the phase of your light.
Student 9: So we have to decide what numbers to put in for the phase?
Teacher: Do you guys understand? It's like a clock, say a 60 second clock. You have to decide if your light is gonna change when the second hand reaches the 1, the 2, the 3, the 4, the 5. Right now everybody's clock changes when it gets to the 12.
Student 9: Everybody could just type in 50.
Teacher: But then you're all switching at the 6 and that wouldn't make a difference.
Student 9: Yeah, we have to make 'em different.
Researcher 2: The question is what would be a good way to do this phase?
Student 3: We should alternate. 0, 50, 0, 50.
Student 7: How 'bout we just put random numbers in?
Student 9: Can't we just do them all the same?
Student 7: That's what we have been doing., we want it different this time. Let's do the random.
Researcher 2: Okay, what do you think will happen if we try random?
Student 7: I think it'll be exactly the same as before – random won't help the traffic flow.
Researcher 1: Okay, why don't you all put in your random numbers.

Students enter a phase number in their calculators and restart the simulation. {{Uri – results?}} In evaluate this "random" strategy the need for metrics or ways of comparing results arises in a natural, contextualized way. In considering possible metrics for traffic, this group of students felt that number of cars stopped was not the best for quantifying results. They worked on creating a metric that would be related to the "length" of a traffic jam.

The class from the Austin area was animated and engaged. Even without the same agent-based modeling background, they begin to articulate strategies motivated by the felt need to develop a coordinated strategy to improve the traffic flow.

Teacher: Has anybody started to think of some ideas like what are you doing at your stop light that you think is working really well? Who has some ideas of why they think maybe their stop light is working better than somebody else's stop light. Anybody have any ideas? Anything that you're trying to do yet? Yeah (pointing to student).

Student 1: Letting one go and then the other go.

Teacher: Okay, so you're letting one go … are you letting it go for a certain amount of time?

Student 1: Nah, just go this and that way.

Teacher: So you're just doing one then enter, two then enter. …

Student 2: Pick a space between the line of cars to turn the light red, so that way, so then all the cars will be stuck together.

Teacher: So get the cars staggered and spaced out and pick a spot between … yes, sir (pointing to a third student).

Student 3: Have it like every place where I saw the cars go like this (gesturing downward) and once they're done have them all go like that (gesturing to the side).

T: So have the down ones green (gesturing downward with fingers extended) and then all the side-to-side ones green (similar gesturing to the side).

These are just some of the strategies students generate. The first strategy is simply alternating the lights at a regular interval. The second strategy looks for open spaces to shoot for in turning the light red in that direction. Other sections of classes at this school articulated what we call a "traffic cop" strategy where you simply look locally to see in which direction there are the most cars at your intersection, and then let that direction go (i.e., like what a traffic cop might do at a busy intersection). Some students discussed the possibility of developing "smart cars". With smart cars there might not be a need for lights, *if* a way could be found to "coordinate" with cars coming from the "other" direction. As was true for the Boston area students, the Austin area students came up with a phase-related strategy for "synch-ing" the lights. The actual classroom exchange related to this strategy highlights some of the pedagogical challenges related to engaging and extending the developing strategies of students. These issues help point to possible future directions for developing the HubNet functionality.

In repeatedly reviewing the tape of the Austin area classroom, it is not clear whether Student 3 meant for his strategy to be only for a particular column of traffic, or whether he, in fact, meant for the strategy to be applied to all the columns in parallel. The significance of the teacher having her fingers extended was to denote all the lanes in one direction working this way and then all the lanes in the other direction. In contrast, the student used only one finger to gesture downward and then the same finger to gesture to the side.

This observation is made not to highlight any shortcoming of the teacher. Rather one take-away from running these activities in classrooms is that the kinds of activity and reasoning generated in relation to these activities is comparatively complex. The pedagogical load for teachers is clearly higher than it might be in a traditional mathematics classroom. Tracking student ideas in real-time as part of the iterative pedagogy associated with using participatory is clearly more challenging than asking students to "simplify 2x+3x" on the board or on a workshop. While the teachers we work with believe there is a clear payoff in that their students are engaged with and making sense of import systems ideas, there is also a greater demand placed on the teacher to make good use of all the artifacts, gestures, and verbalizations of students. In the future development of HubNet functionality we intend to implement new ways of capturing and rendering student-generated artifacts and outcomes.

As part of comparing results from implementing different strategies, the handheld devices (calculators) have significant resident functionality. Data from the simulation can be distributed to the class and then every student can use a set of mathematically meaningful analytic tools (graphs, tables, histograms, etc.) to analyze the results. The flow of information and the location of the tools of analysis does not remain "centralized" in this model. Instead a multi-directional (student to student, teacher to student, student to teacher, etc.) flow and exchange of analyses is supported in the HubNet architecture. In this traffic example, various metrics for measuring the improvement in traffic flow can be developed by students and a set of final recommendations can be developed as a report (or collection of reports) to the mayor. The reports can incorporate elements of both object-based and aggregate analyses. Although on the face of it this traffic activity seems quite distant from the traditional curriculum, it is in the process of creating these metrics that students reach for and/or make sense of traditional metrics. This understanding is deeper not only because the learners must make sense of the mechanics of computing quantities like mean, median and mode, they must also struggle with the meta-issues of which representations or renderings of the data are most useful to the task of preparing a report to the Mayor. Learners must select which quantity or quantities to measure (e.g. wait time at lights, average speed across the city, number of stops, etc.). Not only is understanding deepened, but the top-level question of "What is math for?" is addressed in a way that is interesting and engaging *precisely* because participatory simulations are complex. Traditional curricula assume you must start with procedure for computing before applying them. In the contrast we use dynamicism and complexity of systems like traffic to motivate the "need" for both the formal constructs of the traditional curriculum as well as new concepts related to systems thinking.

PeopleMolecules

Participatory simulations can scaffold student understanding in a wide range of contexts from abstractions, like points on a graph (Wilensky & Stroup, 1999), to the imperceptibly small, like molecules in a gas. A standard component of most introductory chemistry curricula and many introductory physics curricula is the kinetic-molecular theory of gases. A very challenging aspect of this theory is developing insight and understanding related to the distribution of speeds for an ideal gas. When asked about the movement of molecules of gas in the classroom, there is little in students' day-to-day experience that could support any understanding of why the molecules of gas would have differing speeds and why some aspects of the distribution of these speeds might remain constant. Why wouldn't students believe, as many do, that the uniformity of their sensory experience in moving across a classroom extends down to the molecules and that mean the speeds of the molecules are nearly uniform? Or why wouldn't students who *do* have a sense that molecular speeds varying, also assume that there is little or no pattern in the distribution of these varying speed? The goal in developing the people molecules simulation is to have students make sense of two core ideas: (1) that speeds vary for individual molecules and across the population of molecules due to collisions, and (2) that there are, nonetheless, top-level invariances like the distribution of speeds for an ideal gas (the Maxwell-Boltzman distribution). These invariances are related to the uniformity of students' sensory experience in moving around a classroom and allow us to construct macroscopic constructs like pressure and temperature. We have run the PeopleMolecules simulation in a number of different settings. Across these contexts the pedagogical sequence has been similar and the results have been relatively consistent. The account that follows is from a different section of middle school science class in the same Texas school discussed earlier.

Keeping with the pedagogical design discussed earlier, students were first asked what kinds of things they knew about the air in their classroom. Students mention a range of properties from the transparency (e.g., "you can't see it") to the idea that "it has water in it". As part of this initial discussion an interesting debate developed when one student listed as a property of air that, "You can't feel it." Almost immediately another student said, "Yes you can!," and demonstrated this by waving his arm through the air while saying, "You can feel the wind." After a somewhat animated exchange between different factions aligning themselves with one of these two stances, a kind of rapprochement was worked out. You can feel air if you are moving but while you're standing still you can not. For all of these observations, and despite the fact that elastic collisions are typically discussed as part of textbook presentations of kinetic molecular theory, no students made mention of the collisions of molecules as playing a central role in "mixing" the speeds of the molecules. Likewise no mention was made of how a particular kind of distribution of speeds could characterize the molecules in the classroom.

To explore both the role of collisions and how a stable distribution of speeds of gas molecules could emerge, a bounded space for people "molecules" to interact of was created in the classroom. This space was created by encircling a region of the classroom with paper from three-foot roll of butcher paper. Some students held up the "walls" of this container while other students were the "molecules" placed in the container (Figure 7).

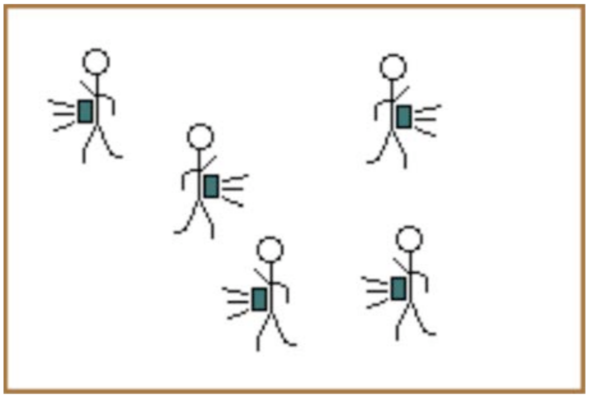

Figure 7: Students moving around and enclosed space as if they are molecules.

Each student molecule carried a calculator connected to a motion detector (Texas Instruments' Calculator Based Ranger [CBR]). As these students moved around in this space their speeds varied. Motion detectors and calculators sampled and recorded each student's speeds out over a fifteen-second time interval. In this way data was collected for each "molecule" (student) in this "people-molecules" gas (collection of students). At the end of the time interval, each calculator was programmed to display an individual histogram of sampled speeds. These individual histograms were then compared. While students were able to identify some similarities in the shapes of the distribution (e.g. "few out on the end" [few samples of relatively high speed]), for the most part they tended to see the distributions as mostly different. Often this sense of difference was judged relative to comparatively minor variances. Consistent with the sense that students often see any variance as meaning there can be "no pattern" overall, the results from individual calculators seemed to be too "rough" to highlight, in a significant way, any top-level consistency. The students were generally quick to express the sense that the changes in speed came from interacting with each other or the "wall." Yet any sense of a consistent global distribution of speeds was not seen as significant relative to the variance.

It was when the results were combined to get the distribution of speeds for the whole people-gas that consistent patterns between trials became more noticeable. The students did notice an overall asymmetric shape that built up toward the middle and then trailed off near the end. Two examples of aggregate results are show in Figure 8.

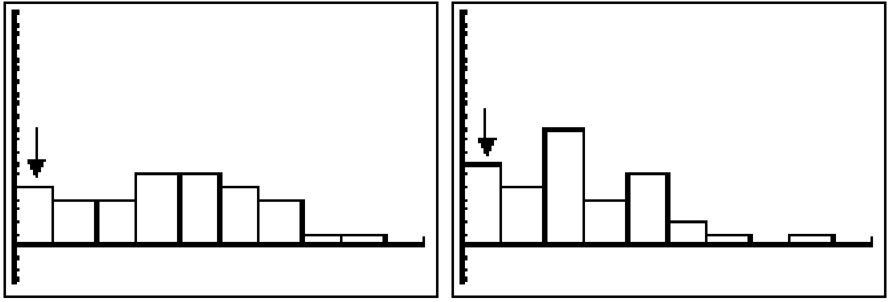

Figure 8: Histograms of "molecule" speeds for two trials of the PeopleMolecules activity.

As has been true for nearly every time we have run this simulation, the aggregate histograms have local maxima near the lowest values of speed (e.g. the regions indicated by the arrows in Figure xx). Students' account of why there are these relatively high incidences of the lowest speeds is that the molecules "slow down" before "hitting" and/or changing directions. People have social conventions for "collisions" that even middle-schoolers observe and these include slowing down. The students themselves advanced the explanation that this local, individual behavior would manifest itself in the collective results as a local maximum for low speeds.

In a later class these PeopleMolecules results were then compared to results from a NetLogo model of an ideal gas. In this NetLogo model the rules for elastic collisions of an ideal gas are programmed in for the interaction of thousands of computational agents simulating the motion of gas molecules (Wilensky, 1999, 2000).

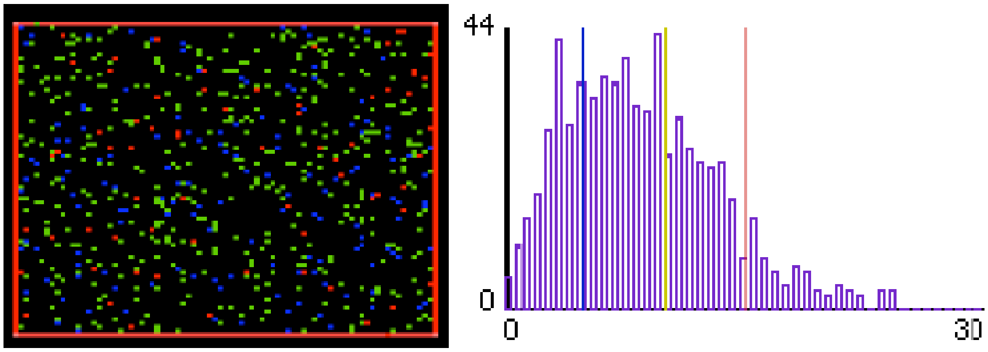

Figure 9: GasLab model of an ideal gas with histogram of speeds closely matching the Maxwell-Boltzman distribution.

This use of NetLogo highlights the sense in which the language is both a powerful environment for agent-based modeling and an environment for authoring network-based participatory simulations, like the Gridlock PSA discussed earlier. The NetLogo model of an ideal gas was introduced to the students as being like a billiard table with lots of "very hard" billiard balls colliding (Figure 9). To highlight the issue of how local rules for collisions (elastic collisions for momentum and energy being conserved) both create variation in the speeds of the molecules and a stable, top-level a distribution all the molecules in the model start off moving at the same speed (with arbitrary headings). This is like having all the balls on the idealized billiard table start off moving at the same speed. There is a significant literature related to using this model alone in learning about gases (Wilensky, 1999, in press). What is new in the context of this paper is the way the results from running the PeopleMolecules participatory simulation interacts with and deepens the student understanding of the NetLogo model and of the Maxwell-Boltzman distribution of an ideal gas.

Before using our simulations with learners we were quite concerned with the limitations of some of them in terms of their fidelity to the systems they represent. We clearly don't want students learning falsehoods. With PeopleMolecules, for example, we clearly didn't want students learning that there was a local maximum of slow moving molecules in real gases. When we ran the simulations like PeopleMolecules we were very pleasantly surprised to find that student understanding was *enhanced* by the contrasts between the simulations and more traditional depictions. While it *is* important to have the participatory simulations be like the system being rendered in at least *some* significant ways and that these ways be closely associated with the learning goals of the activity, it is also the case that many of the most important insights from students come from leveraging the ways in which the simulation is *not* exactly like the "real" thing. The consequence of a simulation not being entirely like the thing rendered turned out to be generative at two levels: (1) The contrasts often highlight significant aspects of the standard scientific models in ways that did, in fact, deepen the understanding of the standard model, and (2) the contrasts also invited the students to develop a sense of agency relative to both the particular models presented and the activity of modeling – the rendering of experience in enactive ways – itself. For PeopleMolecules, the absence of a relative minimum in the Maxwell-Boltzman distribution was noticed and assumed a significance it wouldn't have had if the students hadn't just examined the distribution from the PeopleMolecules activity. Moreover, the contrast or "gap" between the simulation results and the distribution for an idea gas catalyzed an examination of the different ways of running the simulation (e.g. "What if we all tried to move slower?") and the GasLab model (e.g. "What if we they all started moving at a slower speed).

We are continuing to run the PeopleMolecules in schools as there is still much more to learned about the interaction of simulation experiences, understanding of scientific models, and students being able to generate and take ownership of the design and implementation of both simulations and models. A new capability for the PeopleMolecules activity we are beginning to explore in these on-going investigations is the ability to replay the motion data from each student in the NetLogo environment.

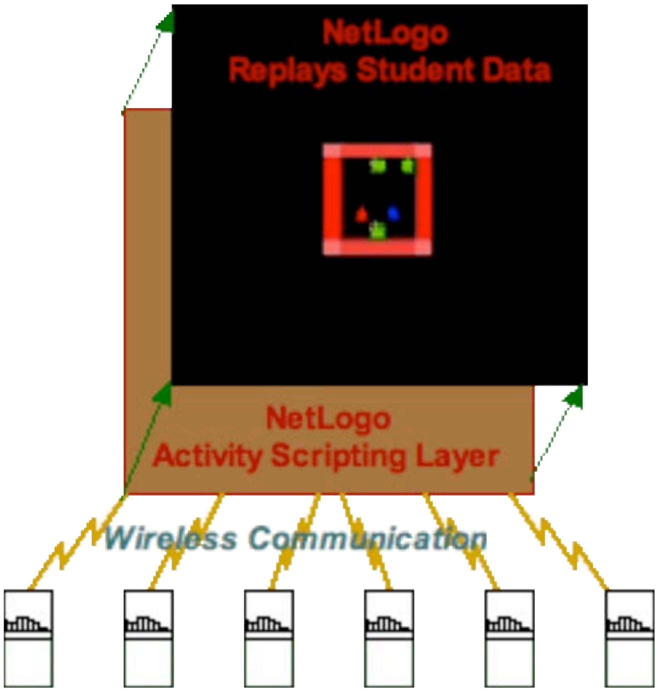

Figure 10: NetLogo Activity Scripting Layer can Import Student Data to be Replayed in NetLogo Modeling Layer

For the replay, the data from each student can be imported into an agent (see colored agents in Figure 10). These agents then would be confined to move in a container where their speeds would come from the student motion data and the directions would be randomly assigned. Agents would also "bounce" of f the walls in the model. The sense is that this re-enactment in the NetLogo environment would provide additional scaffolding between the embodied student experience and the interpretation of the GasLab model of an ideal gas. Although the students would not be controlling the NetLogo agents in real-time like they do in the Gridlock simulation, there would still be the sense in which their embodied movements with the motion detectors were controlling cybernetic agents. There would be a succession of kinds of embodiment from moving around in a room, to having that motion be rendered in a computer model, to having students explore the embodied rules for agents that animate the NetLogo model of an ideal gas. At the level of aggregate analysis there is also a movement from a histogram of motion in a room, to an evolving histogram in NetLogo of the "replay" of their motions, to making sense of the histograms associated with the GasLab model and, by extension, real gas molecules in the classroom.

Future Directions

As indicated above, the HubNet architecture is in a preliminary stage. Significant project resources are allocated to developing HubNet and completing the fully networked architecture. Alongside this iterative design research, we will continue to conduct both implementation and curricular research with successive versions of HubNet. We have begun to design and test a set of PSA using ClassLogo that make use of sophisticated new content domains. This fundamental research is being carried out in economically challenged inner-city schools. Significant resources from the PSP Project are going toward site-based support and innovation. We are working alongside the teachers in targeting and implementing network-based participatory simulations that can transform students' understanding of core concepts of the current curriculum (e.g. the concept of function) even as fundamentally new systems-understandings and content areas are introduced.

In this context, we seek to gain a better understanding of how a PSA can significantly advance student understanding of the unfolding dynamics of systems. We hope to shed light on how learners' intuitive understandings and ways of responding interact with rule-based, embodied (e.g., StarLogoT, NetLogo) and aggregate (e.g., STELLA) modeling environments. Through this design, implementation and curricular research, we hope to further the goal of advancing systems related understanding for *all* students.

Acknowledgements

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