Embodied Learning: Students Enacting Complex Dynamic Phenomena with the HubNet Architecture

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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. This 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* – 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

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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 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).

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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 University with the CCL.

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 that can be used by 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, 199x; Waldrop, 199x; Kauffman, 199x;)

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, 199x; 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 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). 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, 199x).

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 et al, 1978; Mandinach & Cline, 1994); and d) the analysis of systems like gases (Wilensky, 1994; 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 new 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 projected classroom display of the emergent result.

The HubNet architecture has been developed in stages. At present, a workable subset of functionality is implemented. This subset consists of 1) a network of graphing calculators called Odyssey developed in concert with our commercial partner, Texas Instruments. 2) a server, which talks to the Odyssey network and 3) an object-based parallel (aka multi-agent) modeling language, NetLogo, 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. Future versions of HubNet will integrate aggregate modeling languages, such as STELLA, extending the dialogue between object-based and aggregate approaches.

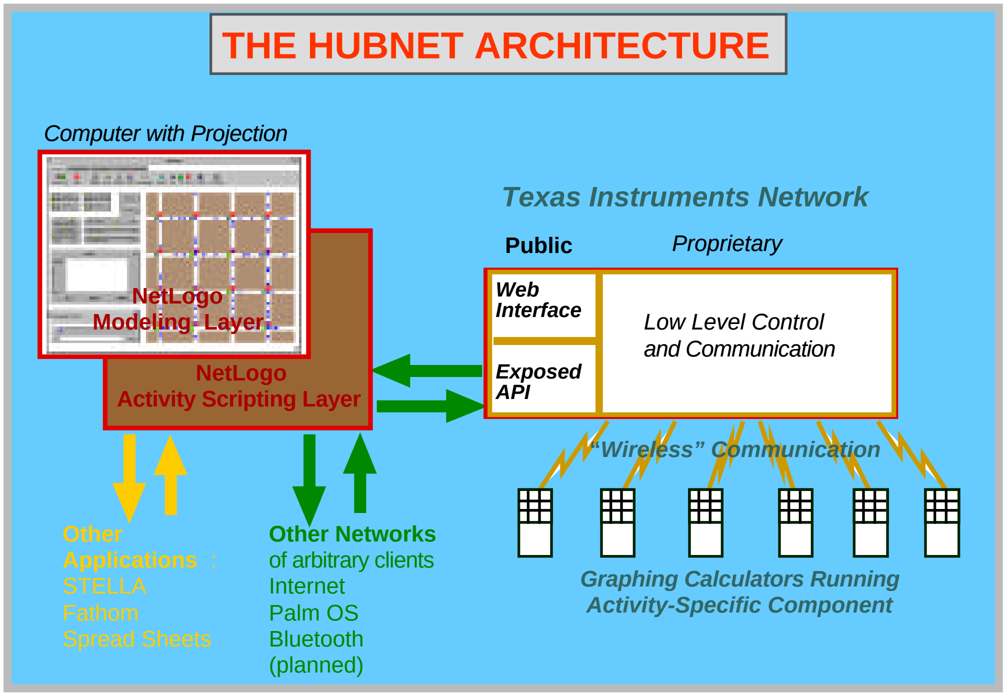

Figure 2: The HubNet Architecture

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 Odyssey network was used. Current versions of Odyssey 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 will be 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 Odyssey 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).

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 commercial TI Odyssey 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.

ClassNet 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.

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. Teachers who, of necessity, feel a great sense of responsibility to a traditional curriculum can still service that curriculum while beginning to explore important elements of systems ideas.

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 are generative. Generative activities are what we describe as “space creating” activities. 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. By participating in

the creation of the space, they are then invited into a conversation about how we might begin to see this space as structured. How might we look across these cases? How might we articulate patterns and ways of operating in this space that deepen our understanding and give us tools for evaluating various possibilities? By creating a range of ways of controlling traffic, students are, in essence, co-developing precisely the texture and contrasts they need to deepen their insights. By creating systems they are invited into conversations about what is a system. Because this generative approach is distinct from the "collapsing" approach of traditional curricular design that most of us have grown up with as students and teachers, it is one of the most challenging ideas for the teachers we have worked with to make sense of. Participatory simulations move in a very different direction from this collapsing expectation and toward a more generative understanding of the traditional domains and of systems ideas themselves. By working with existing participatory simulations and, even more powerfully, by beginning to design their own participatory activities teachers move beyond the limitations of traditional activity design.

We look 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, 19xx, 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*[3] and this stands to improve both student motivation and understanding. Student engagement and sense of

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[3] 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).

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. He has commissioned our class to improve the traffic situation in the city.”

The teacher runs the NetLogo traffic simulation and projects it in front of the class,
The simulation starts running with cars driving east and north through the city. The city starts off with no traffic lights. A graph depicting the number of stopped cars is also dynamically updating. On first impressions, it looks like everything is running smoothly for this city (Figure 3a). The average wait time is close to zero.

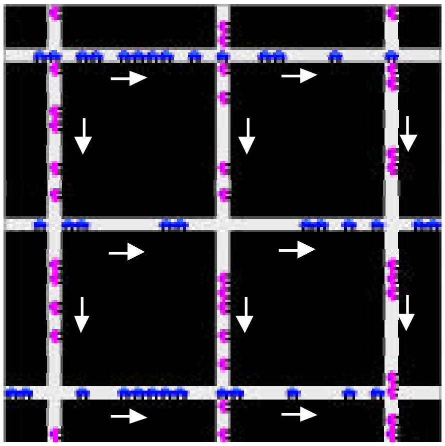


Figure 3a: Traffic flow with no lights.

Figure 3b: Dynamic plot of stopped cars

The problem is that the initial simulation doesn’t keep track of when cars are occupying the same location on the grid. 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 3c). Traffic comes to a complete standstill.

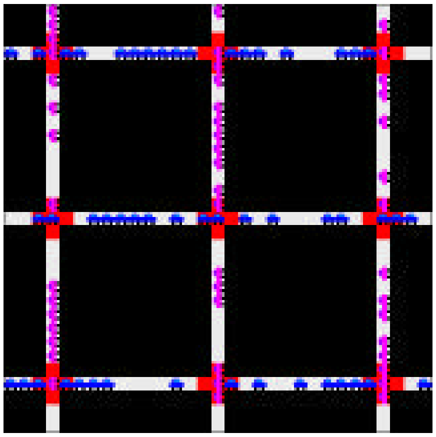


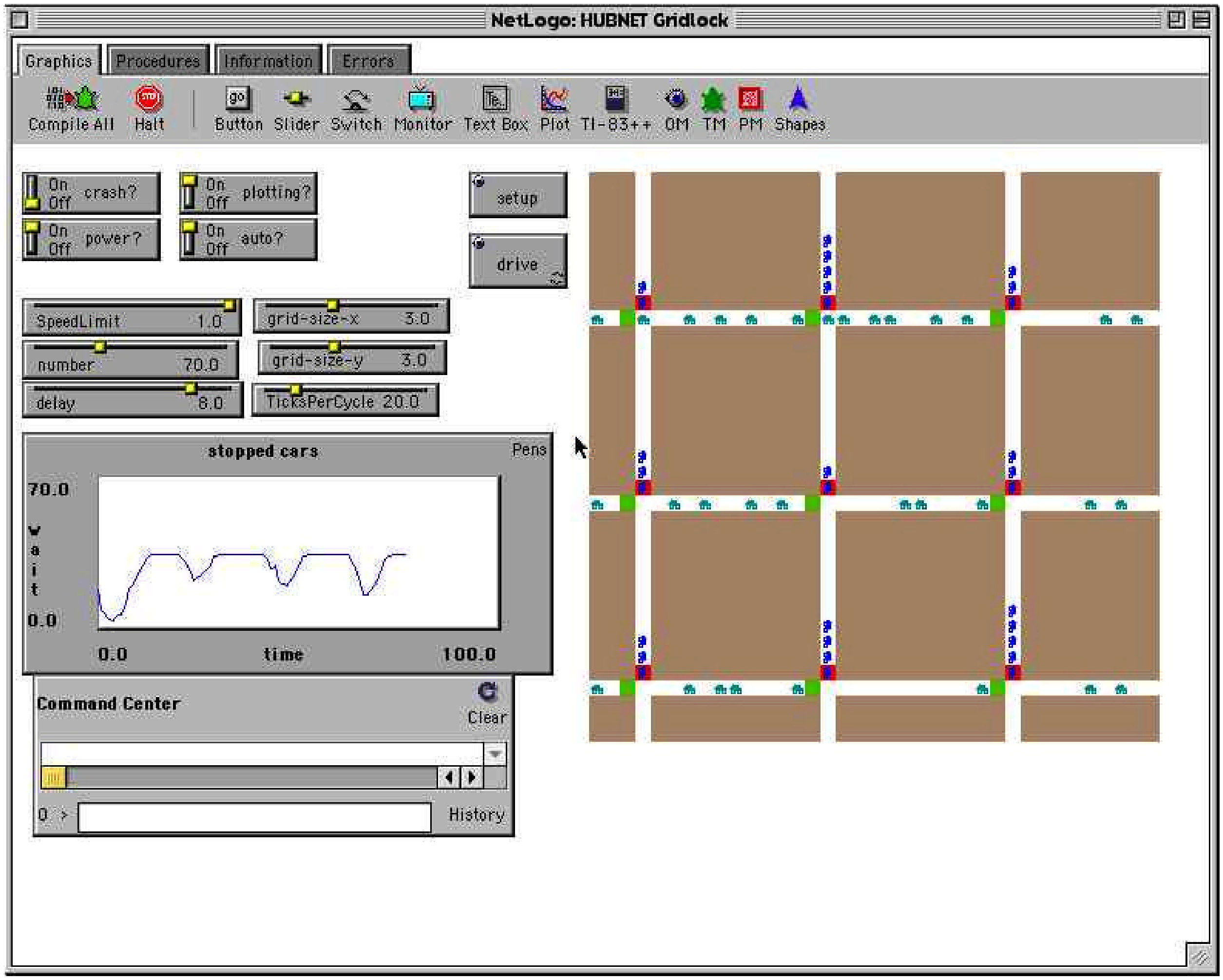
Figure 3c: Accidents quickly result.

The initial introduction of the participatory simulation is completed 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 the one. the one with the traffic light.

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. While many details vary across settings, the description below of one middle school science classroom's experience is in many ways typical of the path that the gridlock activity takes.

We now describe the unfolding of the Gridlock activity in a single period of a middle school science classroom in the Boston area. This 8th grade science classroom had done some modeling work with one of us (Wilensky) using the StarLogoT language, but the period described was the first use of the HubNet system with the class. The teacher had had a little experience with NetLogo and had volunteered to try out the HubNet system in his classroom.

There were 18 students in his class so the teacher configured the NetLogo simulation to have 9 intersections. He set up the desks in the classroom to mirror the geometry of the grid and assigned two students to each intersection.



SpeedLimit 1.0
number 70.0
delay 8.0
grid-size-x 3.0
grid-size-y 3.0
TicksPerCycle 20.0

Figure 3d: The NetLogo screen of the Gridlock PSA

He introduced the activity as described above and then proceeded to place traffic lights at every intersection. He demonstrated how students could control these lights using the up-arrow keys on their calculators. After each student pair located their intersection and practiced changing the lights, he introduced cars into the NetLogo simulation. He asks the class what they see and summarizes their response: “The good news is that there are no accidents in the City of Gridlock. The bad news is that traffic is backing up all over the city (Figure 4)”. He further observes: the average speed through the city is low, the average wait time is high, and “the Mayor would not be pleased”. “Can you help?,” he asks. The Students then explore various ways of controlling their lights.

This phase of the Gridlock activity can be quite noisy and exciting. The students gazed up at the simulation and, when traffic got heavy at their intersection, used their calculators to change the color of the light. There is a built in delay between the time the students press the calculator keys and the time the traffic light changes. As a result of this delay, students need to anticipate when their intersection would back up and press the calculator key a few seconds before. When, either through inattention or a failure to predict a jam at their intersection, an intersection got heavily clogged with traffic, students shouted at the student holding the calculator for the "offending" intersection and told him/her to change the light.

After about fifteen minutes of frenzied manipulation of the lights, the class settles in on a relatively stable solution — no intersection is backed up and the graph of stopped cars is relatively low. The real-time task has been mastered and it is time to complicate the task.

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.

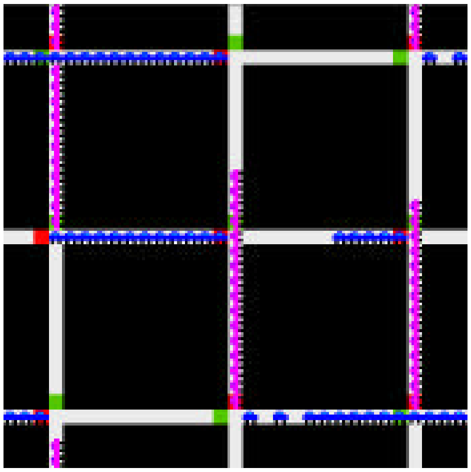


Figure 4. Uncoordinated Traffic

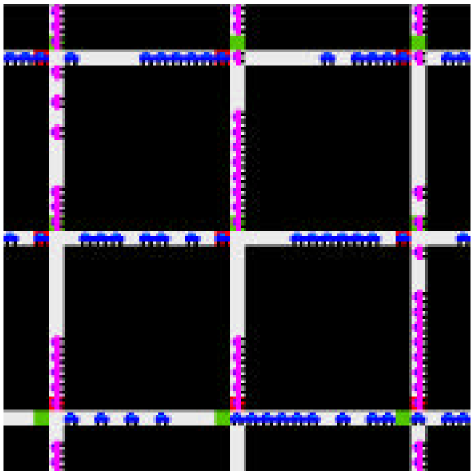


Figure 5. Lights synchronized

One of the strategies is to synchronize the lights with a phase shift. In Figure 5. the lights in the top row turned green in the same direction together, then the lights in the second row waited a few seconds (phase shift) and turned green. This pattern cascades downward as traffic flow in that direction is synchronized. Using the network, data from the various trials can be handed back out to the students. This coordinated approach does improve traffic flow.

It is worth emphasizing that students will actually develop a range of strategies in this participatory simulation. The following are excerpts from the reflective stage in the pedagogical design. This sequence illustrates both the generative potential as well as the challenges of using participatory simulations.

{insert transcript – no time to finish transcribing}

Students often develop a "traffic cop" strategy. Each "light" (traffic cop) would look to see in which direction there were more cars and let that direction go. This strategy has significant counter-intuitive consequences. Other students have begun to explore the idea of "smart cars" where accidents might be avoided if the cars had enough built-in intelligence to figure out if a car coming from the side was going to hit it. The smart car would then take steps to avoid the accident and might be able to do that without having to come to a complete stop (as with a traffic light). As part of preparing a report of recommendations to the mayor of Gridlock, the students must analyze their strategies. Using the network, data can be easily collected and exchanged. The HubNet architecture readily supports the distributed analyses of these different student strategies.

For the purposes of analysis and comparison, the handheld devices (calculators) have significant resident functionality. This means mathematically meaningful tools are available to every student (graphs, tables, histograms, etc.). The flow of information and the location of the tools of analysis do not remain "centralized" in this model, but instead a multi-directional (student to student, teacher to student, student to teacher, etc.) flow and exchange of analyses is supported. 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 will 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. And even before this decision, learners must decide 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 also the macro-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 the formal constructs of the traditional curriculum.

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 still other 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 speeds? Our goal in developing the people molecules simulation is to have students make sense of both the idea that speeds vary for individual molecules and across the population of molecules due to collisions, and the idea that there are, nonetheless, higher-level invariances like the distribution of speeds for an ideal gas (the Maxwell-Boltzman distribution). These higher-level invariances are related to the uniformity of students' sensory experience in moving around a classroom. 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 one meeting of a middle school science class from the greater Austin, Texas area.

In 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 (“you can’t see it) to the idea that “it has water in it”. In this particular classroom, 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 and 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 was created in the classroom in which the people “molecules” could interact. 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.

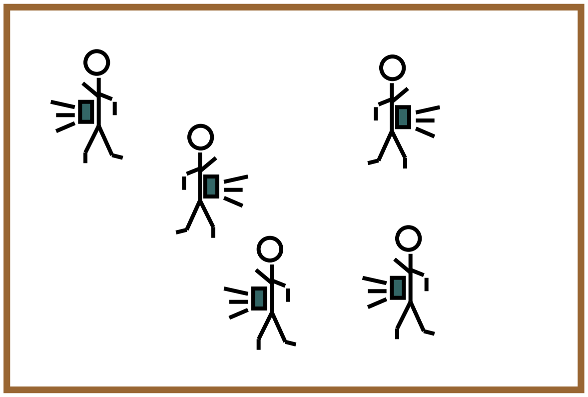


Figure 6a: Schematic of PeopleMolecules PSA

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 macro-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 6.

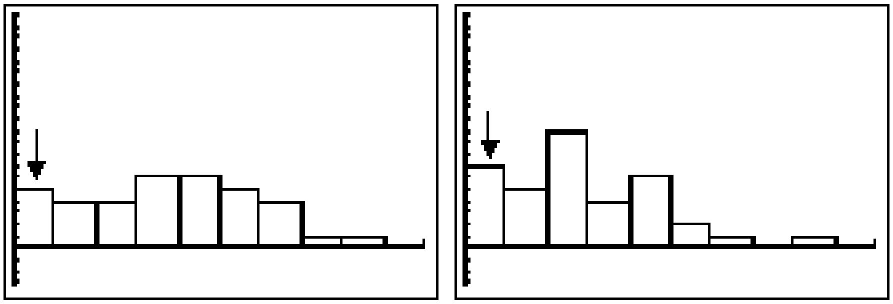


Figure 6b: Histograms of "molecule" speeds for two trials of the PeopleMolecules activity.

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 6). 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; Wilensky et all, 1999).

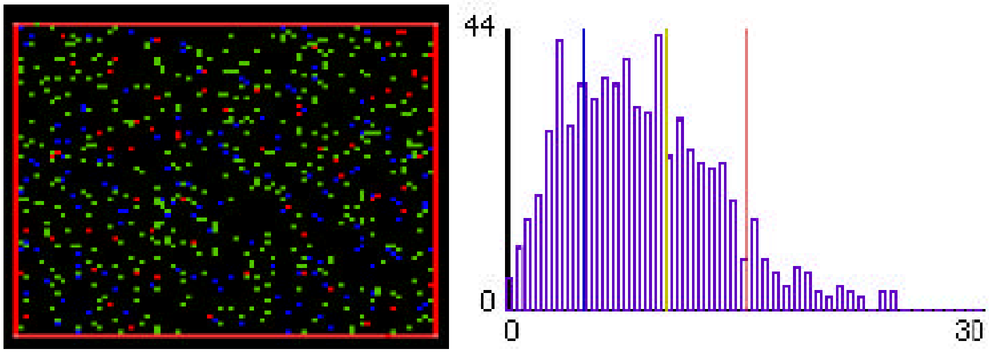


Figure 7: GasLab model of an ideal gas with histogram of speeds closely matching the Maxwell-Boltzman distribution

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. 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, 1993; 1999; Wilensky et al, 1999). 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 slower moving molecules in real gases. When we ran PeopleMolecules we were pleased 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 learn 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.

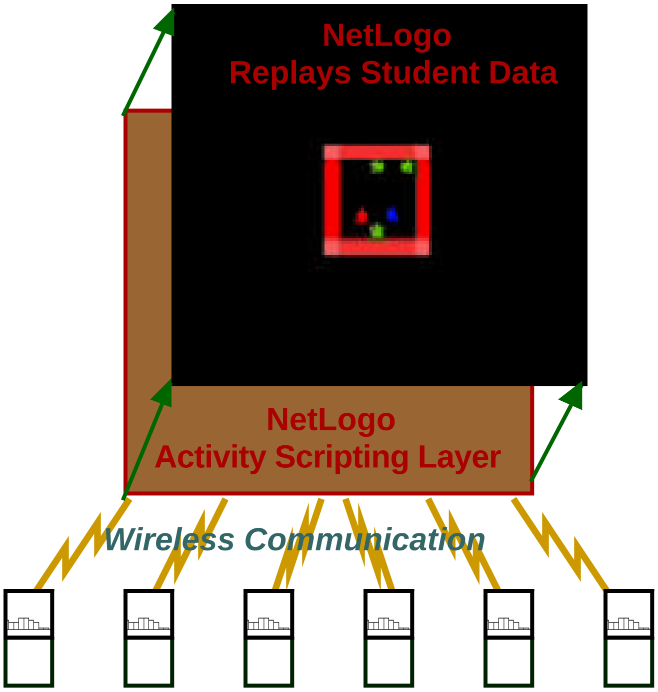


Figure 8: NetLogo Activity Scripting Layer can Import Student Data to be replayed in NetLogo Modeling Layer

For the replay, the data from each student can be imported into an agent. 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" off 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 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 object-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.

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