Gas Laws and beyond: Strategies in exploring models of the dynamics of change in the gaseous state

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ABSTRACT

How can we characterize the ways in which students explore computer models to search for information? In the Modeling Across the Curriculum project, we enable students' exploration of computer models that are embedded in a supporting script. The Connected Chemistry^{TM} learning environment is one such model-based curricular unit. Connected Chemistry employs multi-agent NetLogo (Wilensky, 1999a) models to empower the students' manipulation and observation of chemical "entities" at the molecular level as well as the resulting aggregate patterns. The first Connected Chemistry unit is on the topic of gases: Gas laws, and Kinetic Molecular Theory. We provide an analysis of student's explorations within computerized models, as derived from computer logs of their actions and the models' changing properties and learning contexts. We have conducted four studies into the patterns of students' model exploration. The studies show the following: (a) Students employ four distinct patterns of model exploration; (b) Students are consistent in their use of a specific pattern; (c) Some specific features of these patterns change when the goals change; (d) More than half of the students take advantage of the affordances of more powerful exploration tools to improve their search for information; (e) Almost half of the students adapted their exploration strategy to the underlying mathematical relationships. The results are discussed in terms of science inquiry skills, styles in information search in digital spaces and the educational implications of these findings. To demonstrate our analysis of the extensive log files, we present an analysis of the learning path of one student engaged in Connected Chemistry activities. We then discuss the planned future work in tying in these findings with the students' prior knowledge and learning outcomes.

INTRODUCTION

Learning about gases through model exploration

A body of science education literature points to student's misunderstandings of the gaseous phase of matter (Lin & Cheng, 2000; Maz & Perez, 1987). Some of these misunderstandings can be related to what Wilensky and Resnick call "levels confusion" (1999), where the properties of the macro-level are incorrectly ascribed to the micro-level (in the particular case of chemistry). The macroscopic properties of gases are easier to experience and perceive, such as when a kettle boils or a coke bottle produces a hiss when it's opened. However, the microscopic particles that are moving, colliding and bouncing off the walls are invisible. The literature reports a variety of student's non-standard conceptions about gases such as ordered packing of molecules and weightlessness of the gas. Lin and Cheng (2000) describe high-school students' difficulties in understanding Kinetic Molecular Theory as it applies to gases: molecules are pushed down, molecules stay away from heat and molecules expand when they are heated. All three can be related to our macroscopic daily experiences: the force of gravity pulling objects towards the earth, boiling water rising out of a pot and expansion of matter upon heating. Mas and Perez (1987) have found that high-school students regard gases as weight-less, reasoning from their observations that gases rise, and inferring that they therefore cannot have weight. Similar problems have been reported in a variety of scientific domains, such as genetics (Marbach-Ad & Stavy, 2000) and basic electricity concepts (Frederiksen, White & Gutwill, 1999).

The learning research community has recognized a disconnect between conceptual and algorithmic understandings of Chemistry (e.g., Kozma et al, 1990; Niaz & Robinson, 1992; Stieff & Wilensky, 2003). For example, Berg and Treagust (1993) point to the minimal use of qualitative relationships regarding teaching the gas laws both in a variety of textbooks they analyzed and in teaching approaches in schools. Students may be capable of solving problems that involve the procedures commonly taught in science classes. However, they do not necessarily do as well when approaching a similar problem that requires more qualitative, or conceptual reasoning.

A fruitful way of approaching the problem of bridging the conceptual and symbolic forms of representing chemical phenomena is to use computer models that employ multiple representations and that have affordances that enable connecting the representations (see 4M:Chem, Kozma et al, 1996). Frederiksen, White & Gutwill (1999) have employed a variety of conceptual models to design computer simulations to help students connect the different levels that can be used to describe basic electricity: a particle model, a circuit model and an algebraic model.

Wilensky and colleagues (Wilensky, 1999b; 2003; Wilensky, Hazzard & Froemke, 1999) have shown that NetLogo models can be powerful avenues for learning about gases and, more generally, about statistical mechanics. In their studies, students used the GasLab (Wilensky, 2000) package. Students were involved at three levels: exploring existing GasLab models, modifying those models, and constructing new such models.

The work reported here builds upon this previous work, but differs in that all the students are involved only at the exploratory level and that their explorations are guided and constrained by a script. The script is designed to guide but also to enable freedom and exploratory flexibility. However, the Connected Chemistry models do enable students to view (and modify) the underlying rules that generate the model behaviors. The affordance for students to connect the observed phenomena with the mechanism or rules underlying the model enables students to view the model as modifiable by them and not a prepared “movie” selected by the designers.

Connected Chemistry activities

Chemistry is a natural domain for an agent-based approach, as all chemical phenomena emerge from local interactions among a multitude of interacting individual molecules. In the Modeling Across the Curriculum project, we enable students’ exploration of computer models that are embedded in a supporting script. The Connected Chemistry learning environment (Levy & Wilensky, 2004; Levy, Novak & Wilensky, 2005; Stieff & Wilensky, 2003) is one such model-based curricular unit. Connected Chemistry employs multi-agent NetLogo (models to empower the students’ manipulation and observation of chemical “entities” at the molecular level as well as the resulting aggregate patterns. In this project, the models are embedded within a Pedagogica ™script (Horwitz, 2002) that structures the interaction of the students with the models, guide the model exploration as well as asking students questions about their exploration and findings. The first Connected Chemistry unit is on the topic of gases: Gas laws, and Kinetic Molecular Theory. The models used in the current project are a modified version of those originally created for the GasLab curriculum (Wilensky, 1999b).

The first set of activities in the Connected Chemistry curriculum is on the topic of gases: Gas laws, and Kinetic Molecular Theory (KMT). Kinetic Molecular Theory describes the behavior of individual particles (e.g., particles move in straight lines, they elastically collide with each other and with the walls). Gas laws describe the relationships among properties of the system of particles as a whole, when it is in equilibrium (e.g., Boyle’s Law: the relationship between the volume of a box and the pressure inside, when temperature and the number of particles are constant). In addition to the traditional chemistry content, our curriculum also targets several important chemistry-related ideas: (a) Modeling: how a model is constructed, its assumptions, affordances and limitations, its relation with the target real-world phenomenon; (b) Thinking “from the molecule up” by focusing on micro-to-macro descriptions, transitions and connections; (c) Focus on processes of change in the system, such as perturbation and equilibration; (d) Mathematical modeling, deriving equations from data obtained through the students’ NetLogo model explorations.

More generally, the chemistry topics are set within a wider perspective of complex systems. The domain of “complex systems” has evolved rapidly in the past 15 years, developing novel ideas and tools, and new ways of comprehending old phenomena, such as weather systems. Complex systems are made up of many elements (sometimes described as “agents”, in our case, molecules), which interact among themselves and with their environment. The interactions of numerous elements result in a higher-order or collective behavior. Although such systems are not regulated through central control, they self-organize in coherent global patterns (Holland, 1995; Kauffman, 1995; Resnick & Wilensky, 1993). These patterns are often counter-intuitive and surprising.

The Connected Chemistry unit consists of a sequence of seven activities. The sequence of activities is as follows:

(1) **Modeling a Tire**: A rule-by-rule construction of the gas model, leading up to a focus on the Kinetic Molecular Theory (KMT) assumptions.

(2) **Changing pressure**: Introduces the concept of pressure, elaborating on processes of change, delays between perturbing the system until the system reacts and then re-equilibrates, relations between the randomness of the gas particles' motion and the stability of pressure.

(3) **Experimenting with particles**: New tools are offered in this activity – the use of several NetLogo commands to change the particles' properties, enhance and change the visual representations; propagating global effects from a local change; The students design and conduct an experiment of their choice, determining their course of action and using NetLogo commands to conduct their exploration.

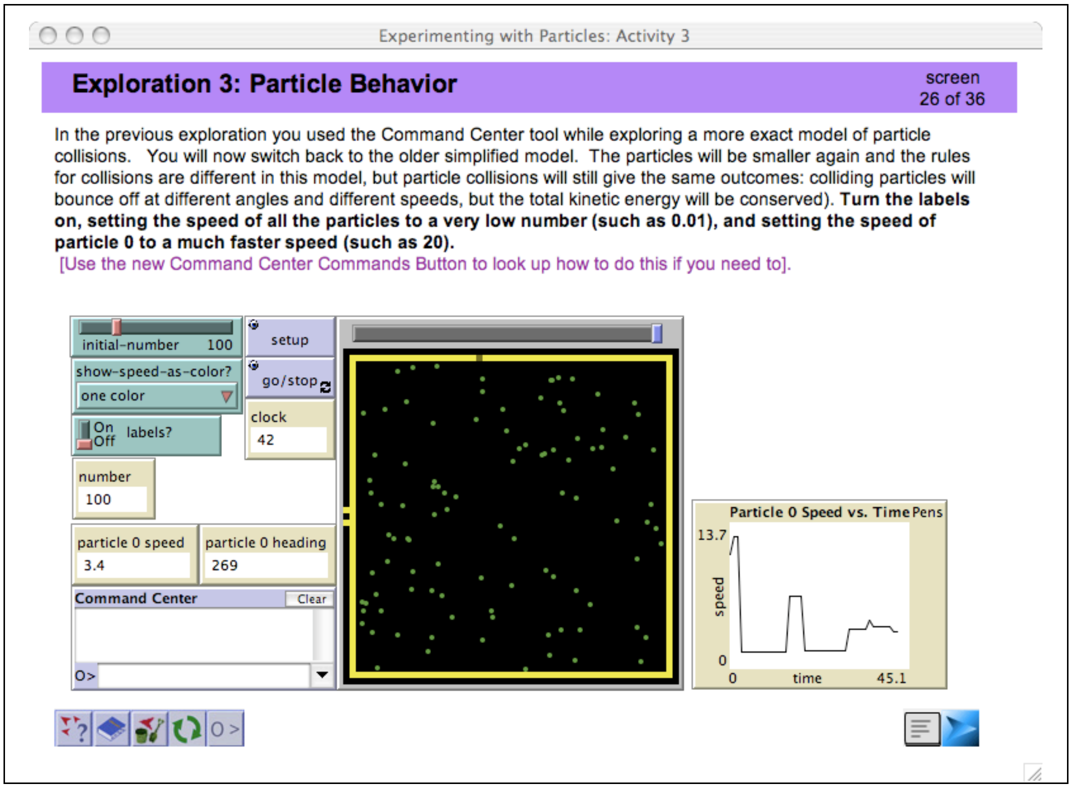
(4) **Number and pressure**: The relationship between the number of particles in a fixed container and the pressure is explored, both qualitatively and quantitatively – deriving the equation that relates the two variables.

(5) **Temperature and pressure**: The concept of energy is elaborated upon via the changes to the gas temperature; the qualitative and quantitative relationship between temperature and pressure is investigated.

(6) **Volume and pressure**: The concept of pressure is further explored in this activity, as it relates to the area of the container's surface; the qualitative and quantitative relationship between the two variables is probed and summarized.

(7) **Ideal gas law**: Through both open investigation of a more complex gas model, and a guided mathematical derivation, the unit culminates in the Ideal Gas Law.

To illustrate the curriculum, we portray a sample screen that is part of the third activity "Experimenting with particles" (see Figure 1). Several explorations throughout the curriculum call attention to microscopic particle behaviors and their relation to the system-wide variables. In this activity, the students control the initial speeds of the gas particles, practically "freezing" them in place, creating a low pressure in the system. They are using simple NetLogo commands to determine the initial state of the model. They then increase one particle's speed tremendously and observe its speed over time. They observe both the overall aggregate behavior in the "world" and the changing speed of the initially-fast particle. In the forthcoming run, the students observe how collisions between the particles re-distribute the speeds, while the system gradually equilibrates. In later screens, the related pressure is investigated, conservation of energy is introduced and explored.



Experimenting with Particles: Activity 3

Exploration 3: Particle Behavior

screen 26 of 36

In the previous exploration you used the Command Center tool while exploring a more exact model of particle collisions. You will now switch back to the older simplified model. The particles will be smaller again and the rules for collisions are different in this model, but particle collisions will still give the same outcomes: colliding particles will bounce off at different angles and different speeds, but the total kinetic energy will be conserved). **Turn the labels on, setting the speed of all the particles to a very low number (such as 0.01), and setting the speed of particle 0 to a much faster speed (such as 20).**

[Use the new Command Center Commands Button to look up how to do this if you need to].

initial-number 100

show-speed-as-color? one color

labels? On Off

number 100

particle 0 speed 3.4

particle 0 heading 269

clock 42

Figure 1: A screen from the “Experimenting with Particles” activity

To summarize, we have presented the rationale for the Connected Chemistry curriculum, its sequence of activities and an example activity. Through the exploration and manipulation of models, which enable dynamic views of both micro- and macro-level phenomena, we afford a causal understanding of the content of gas particle behavior and gas laws.

Students’ exploration of NetLogo models in the Connected Chemistry curriculum

How can we characterize the ways in which students explore computer models to find needed information? Do the types of goals that guide their exploration affect these characteristics? Is the path of exploration affected by the affordances of the model’s interface tools? By the kinds of mathematical relationships governing the model’s target phenomenon? These questions are explored in a sequence of four studies.

A unique affordance for the research on learning within this environment is the intensive logging of students’ actions. One of the exciting opportunities in the Modeling Across the Curriculum project is to virtually “observe” thousands of students as they manipulate models and interact with the embedding scripts. Students’ work with the Connected Chemistry models and scripts is collected in logs of their activities, both their text-based activities as well as their actions in manipulating the models and also the model’s state and behavior. This intensive logging generates a very large corpus of “click-data”, and answers to open-ended and closed questions, for each student. We provide an analysis of the students' model explorations, as derived from computer logs of their actions as they changed parameters and conducted experiments in the Connected Chemistry models. A conjecture of our project is that this data can be mined for features and patterns that reveal important characteristics of the students' exploration and learning. To do so most effectively we are developing automated tools for exploring and extracting patterns from the data. We provide an analysis of students' explorations within computerized models, as derived from computer logs of their actions and the model's changing properties. Through logging the students' actions with the models, we can search for patterns in the students' investigation. In the future, will report on their relation with the text-based answers, reflecting prior knowledge, knowledge-in-construction and learning outcomes.

The MAC project consists of several different model-based curricular units. Each of these units was developed independently and can be characterized along a dimension of open-ended-ness. The Connected Chemistry unit is generally the most open-ended of these with many free-form explorations. This presents a particular challenge for analysis of the logs as the students can engage in a wide range of possible actions. In this paper, we focus on the students' exploration of the models themselves.

Framework for studying model exploration patterns and their relation to learning

A framework (see Figure 2) has been constructed to plan the logging and analysis of the data regarding the students' model explorations, as well as their relationship with the students' knowledge and learning. It is based on several key features that make up inquiry in science, as well as a learning and educational perspective:

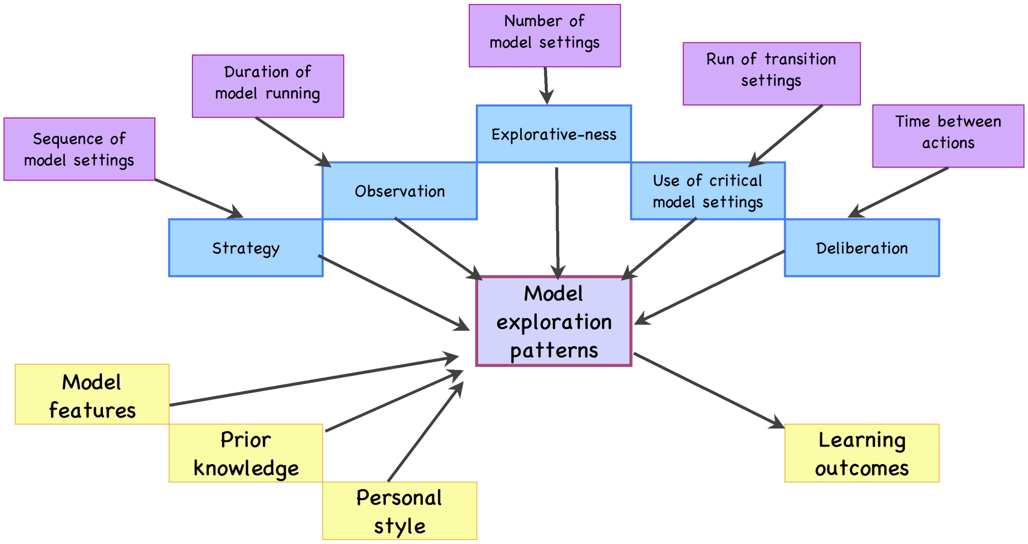


Figure 2: Framework for analyzing students' activities with the Connected Chemistry models, and their relationship to learning outcomes.

Prior knowledge, personal style, and learning outcomes

The anchor and focus of this framework is related to our current investigation: patterns in the students' exploration of computer models. Within the wider agenda of the MAC project, we wish to relate these patterns to the students' prior knowledge, paths of learning and learning outcomes. Prior knowledge may affect the way a model is explored. For example, it is plausible that knowing more about a domain shortens the exploration time, as the student focuses on a few key settings that provide information regarding a specific question. In addition, we assume that personal styles in navigating the model parameter space may impact the way students approach the models in their quest for information. For example, a person who tends to plan ahead and deliberates before taking action will exhibit longer durations between actions. Our framework connects the students' exploration patterns with their resultant learning, or learning outcomes. For example, it is possible that a "click-happy" student, who makes several changes to the model, but spends little time observing its behavior, will not extract enough information from the model exploration to gain a deeper understanding.

What is a student's exploration pattern made up of? In our analysis of these components, we bring in several perspectives: perceptual learning, motor actions, strategies in problem-solving, as well as conceptual issues related to the particular domain and task.

Model running time, observation and perceptual learning

For learning to occur, new information needs to enter the cognitive system and interact with existing knowledge (Samuelson & Smith, 2000). Perception involves the detection and interpretation of sensory stimuli. Perceptual learning is described as a relatively permanent and consistent perceptual change of an array of stimuli, following practice or experience with the array (Gibson, E.J., 1955, 1969, 1988, 1991); as relatively long-lasting changes to an organism's perceptual system that improves its ability to respond to its environment (Goldstone, 1998); or – as a discriminating process in which "blurry" impressions are sharpened, differentiated and integrated (Werner, 1957). During learning, perception shifts towards greater correspondence between what is perceived and what is reality.

Observation is a necessary prerequisite for perceptual learning to take place. We cannot assume that if a student spends more time observing a model, these processes of perceptual learning will actually take place; however, it is plausible that when a students spends more time observing the model while it's running, the probability that such learning will occur is increased.

From the logs of the students' model manipulation, we can obtain the duration of a model run. It is probable that the duration of the model runs is related to the time the student actually spent looking at the model. Thus, our gross measure for model observation durations is the time recorded in the logs during which the model is running.

Time between actions and deliberation

Action is defined as motion with intention (Piaget, 1972; Bruner, 1973; Searle, 1981; von Hofsten, 1995), and as such it is distinct from motion alone. Fischer (1980) defines action as the active control of sensorimotor sets, adding the importance of control. The hands serve as channels supporting flow in two directions: enlarging desires into the world (performatory actions) and bringing knowledge from the world (exploratory actions) (Gibson, E.J., 1988; Bruner, 1973; Uzgiris, 1983; McCullough, 1996). While the latter concerns collecting information from the environment, the first is aimed at changing it. In action, we learn the world through feedback from the objects on which we act, so that agreement increases between perception and the world (Frese & Sabini, 1985; Searle, 1981).

The students' actions with the model are exploratory, in that they provide new information about the model's behavior. These actions are organized around distinct functions. For example, exploring the effect of the volume of the box upon the pressure, which the gas particles exert inside the box, involves stopping the model, moving the wall and running the model once more.

In the logs, each action taken in the model is registered. The average time between actions is used as a coarse measure of deliberation. For example, a quick succession of changes to the model could reflect little planning (aka "click happy"). Longer durations between actions on the model reflect planfulness and deliberation.

Goals, sequence of settings and exploration patterns

A problem can be defined by its conditions: (a) a goal; (b) a barrier that prevents direct access to the goal (Thorndike, 1911, in Rowe, 1987); with Simon (1978, p. 272) adding another condition: (c) attempt or commitment to achieve the goal. Problems can be characterized in different ways: the amount of knowledge needed to solve them (knowledge-poor, knowledge rich, Eysenck & Keane, 1990), the degree to which they are defined (well-defined, ill-defined, wicked, Simon, 1978) and according to the thinking skills that are operated in the process (e.g. Greeno, 1978). Knowledge-rich situations are more difficult to characterize and study because of the amount of knowledge and the variety of ways in which it can be implemented. "Problem-solving strategy" is a term used to describe the way in which an individual chooses a step among all those possible in constructing a solution path towards a target state.

In the Connected Chemistry curriculum, different goals are presented to the students in relatively knowledge-rich problems. One type of goal is discovering *qualitative relationships* between variables, such as volume and pressure, in terms of "more", "less", "increase" and "decrease". Another type of goal involves noticing *distinct model behaviors in a particular regime* of the parameter space. For example, in exploring "how is pressure determined in the model?", the student would benefit by setting a small number of particles in the box and connecting their hitting the wall with zero and non-zero values in pressure monitor. Another type of activity involves collecting data in order to derive a *quantitative relationship* (e.g., Boyle's law). Each of these activities is framed by a different goal. Different goals may encourage different strategies in exploring the model. The open-ended form of some of these problems makes them ill-defined; other problems are more highly structured, and would be termed "well-defined" problems.

We examine the impact of the different goals on the students' exploration patterns. In the logs, each new state of the model following a change in the model is recorded, e.g. the box volume set by the student as she investigates the relationship between volume and pressure. We examine these states as a sequence of settings the students employ in their exploration. We notice their order and their relative magnitude along a time-line of the students' investigation.

Domain specific features of model exploration

In the more general domain of complex systems, as well as the specific topic of the complex gas particles system explored in the Connected Chemistry curriculum, {other aspects of the exploration become important.??}

We incorporate two features in the framework, which are related to complex systems. One is the <u>richness</u> of the exploration, as reflected in the number of different settings, which a student employs. The other is the use of <u>critical settings</u>.

The behavior of a complex system is not linear. For example, in a rigid box when more and more particles are added (or pumped in), the system does not respond in similar ways to different additions. When there are few particles in the box, they are virtually independent of each other, each colliding with the wall, barely colliding with each other. In this regime of the parameter space, one can say that the "whole is the sum of its parts". However, beyond a certain density, or critical value, the collisions or interactions among the particles become more dominant. At this point, the speeds and paths of the particles are not determined solely by the box and their own properties; but also by their energy-and-momentum-conserving interactions with other particles in the box. We can see the distribution of particles' speeds in the box as reflecting such non-linear behavior. When many more particles are added in the box, we can see additional departures from previous model behaviors. At some point, the collisions become so dominant, that a single particle may be "trapped" in a smaller section in space. At this point, a "division of labor" among the particles emerges. Some particles are close to the wall and keep hitting it repeatedly, raising the pressure. Other particles seldom reach the wall and do not contribute to the overall group pressure.

While we explicitly incorporate only some of these principles in the curriculum, they are all "out there" in the models and can be explored by the students. Several strategies can benefit by noticing these features of the model. For example, moving in small intervals through the parameter space can expose the points at which the model departs from one behavior to another.

In capturing the students' model settings, we can see how many runs were made. By looking into their specific values, we can discover whether different regimes were accessed. In the current paper, we analyze only the number of different runs. We intend to investigate the behavioral regimes and critical settings in a future analysis.

Focus

Based on our theoretical framework, four goals guide this investigation:

(a) Characterizing students' model exploration (studies I, IV)

(b) Describing how these patterns may change when the goals are varied (studies II, IV).

(c) Analyzing the impact of different tools' affordances on the students' exploration patterns (study III).

(d) Comparing students' exploration of the model's parameter space, when different mathematical relationships underlie the target system's behavior (study IV).

METHOD

Sample

As part of the Modeling Across the Curriculum project, the Connected Chemistry curriculum has been implemented in twelve school districts.

In this study, a small number of high-school chemistry students were randomly selected from three schools that had engaged in the Connected Chemistry activities. Two schools are member schools in the Modeling Across the Curriculum project; one school is a lab school in the project. In Studies I and II, 6 students were selected. In Study III, 30 students were selected. In Study IV, 35 students were selected.

The conclusions from this work are based on a small data-set and are meant to show what is possible to learn with Connected Chemistry. Further research is needed with larger samples to determine what typical learning results might be. The automated investigation tools are currently being finalized and tested, and will shortly reveal results for the large-scale set of data, we have collected.

Data collection

We have gathered a large corpus of data, recording students' responses to both multiple-choice and open-ended questions, as well as student "gestures" as they interact with the computer models. In this paper, we focus on the latter – what characterizes the students' exploration of the Connected Chemistry models, themselves.

Analysis

In logging the students' activities in the Connected Chemistry environment, we collect each action the student takes: multiple-choice and free-text answers, a well the NetLogo models manipulation. Thus, we have information on the following: (a) initial settings; (b) pressing and un-pressing a button; (c) change in a slider or a switch; (d) entering a NetLogo command in the Command Center; (e) Slowing down the model; (f) states of the model when any action is taken.

These make up the data, which feeds into the four studies.

The process of extracting the information in these studies was performed manually. We are currently in the final stages of automating the process. Due to the manual "mode" of analysis, and the large file size (~400 pages/half an hour of activity), our samples are small (between 6 and 35 students). Once full automation is achieved, we will be able to rapidly analyze the large data samples we have collected.

In our first pass analysis, we extract four statistics from each activity for each student:

(1) Successive settings in running the model: These are portrayed as temporal graphs of the settings, from which patterns are extracted.

(2) Observation time: The time observing the model as it is running (total, per setting). We are aware the students are not necessarily looking at the model while it's running. We have new unanalyzed data, of many students' videotaped activities with the models, which we will compare with the logs. This information will be used to make a better assessment of true observation time.

(3) Average time between actions: Each action taken in the model (e.g. pressing a button, changing a slider, moving a switch) is recorded. The average time between actions is calculated.

(4) Number of runs: The overall number of settings employed by the student.

Description of the studies and their analyses will be combined with a portrayal of the results.

Setting: Computer-based activities in the science classroom

The students engaged with 5-6 40-minute activities on the topic of gases: Gas laws, and Kinetic Molecular Theory (KMT). The activities are described in the introduction, and elaborated upon in a description of the results.

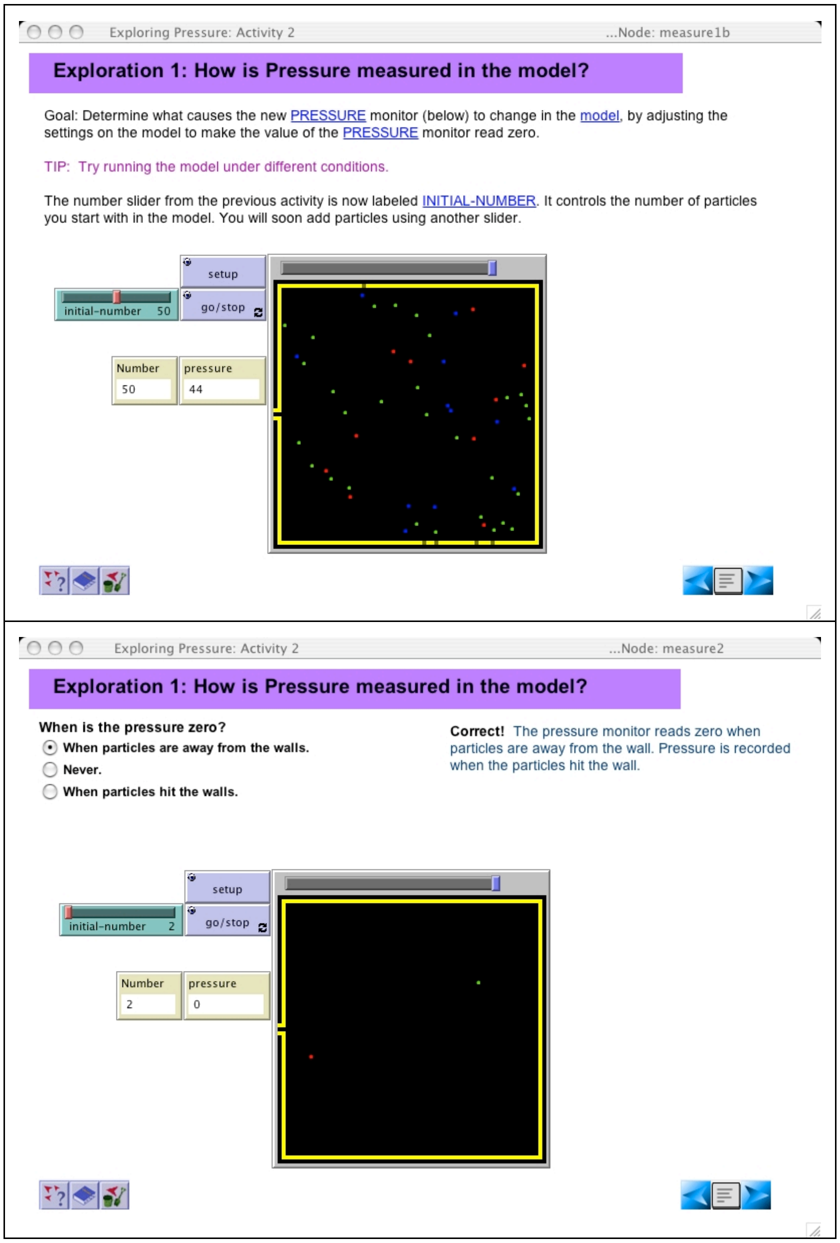
RESULTS

We have conducted five studies into the patterns of students' model exploration:

1. Study I: Patterns in exploring models (part A)
2. Study II: Patterns and goals
3. Study III: Patterns and tools
4. Study IV: Patterns and goals (Part B), Mathematical underpinnings
5. Study V: Individual pathways

Study I: Patterns in exploring models (part A)

In this study, our goal was to understand students' patterns of exploring models when they are engaged in a relatively "open" activity, which allows comparatively free exploration. Three distinct exploration patterns were detected.



Exploration 1: How is Pressure measured in the model?

Goal: Determine what causes the new PRESSURE monitor (below) to change in the model, by adjusting the settings on the model to make the value of the PRESSURE monitor read zero.

TIP: Try running the model under different conditions.

The number slider from the previous activity is now labeled INITIAL-NUMBER. It controls the number of particles you start with in the model. You will soon add particles using another slider.

initial-number 50
Number 50
pressure 44

Exploration 1: How is Pressure measured in the model?

When is the pressure zero?
● When particles are away from the walls.
○ Never.
○ When particles hit the walls.

Correct! The pressure monitor reads zero when particles are away from the wall. Pressure is recorded when the particles hit the wall.

initial-number 2
Number 2
pressure 0

Figure 3: Connected Chemistry "Changing pressure" screen-shots that are analyzed in Studies I and II.

We illustrate the patterns by examining two screens (see Figure 3) in one of the early activities: "Changing pressure". Within the activity, we look into the first section that engages with the following idea: the pressure of a gas in a container (macro property) is related to the gas particles hitting a surface, the walls in the container (micro behavior). One screen that introduces the model and some of its new features precedes the focal screens. In the focal screens, the students are asked to make the pressure monitor read zero. Possible solutions are either having no particles in the container, so that the pressure is always zero; or having very few particles in the box, so that the pressure sometimes reads zero. Thus the target in the parameter space is a small number of particles.

In the model, the students can change only one setting: the number of gas particles in the box. We classify this activity as relatively open, since the students can select any value for this setting. Thus, the feature we focus on here is the sequence of values they set in successive runs of the model for the number of particles.

The students spent an average of 1:55 (0:22 SD) minutes in the section. Among the six students, we have found the following three patterns. The characteristics are derived from the graphs of the succeeding settings and from the Table 2 in Appendix E, which notes observation time (overall, per run), time per action and number of runs.

We can see that all the patterns eventually reach a low number of particles. However, the path taken towards this goal state is different for different students. As seen in Figure 4, three distinct patterns were observed: direct, incremental and oscillating between low and high values. Additional features co-occur with these patterns. The “straight to the point” pattern is one in which the actions are made after longer times, and each run is observed for longer times, even though the number of runs is very small. The “homing in” pattern approaches the goal state in steps, each succeeding step smaller and closer to the target. This pattern can be seen as “click-happy”: actions are very close together in time, the student spends little time observing the results of each run, even though the number of runs is greater. The “oscillating” pattern describes moving back-and-forth between the target state and its other pole: large numbers. It is associated with closely-spaced actions, short observation time, which is complemented by longer overall observation time as a result of the larger number of runs.

Thus, the main conclusions from this first study are:

1. In a relatively open environment, students display three distinct patterns regarding the succession of settings they employ: “straight to the point”, “homing in” and “oscillating.
2. These patterns co-occur with different values regarding the number of runs they undertake, the rate at which they act upon the model and the time they spend observing it.

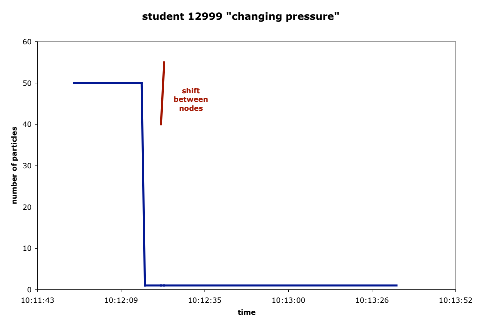
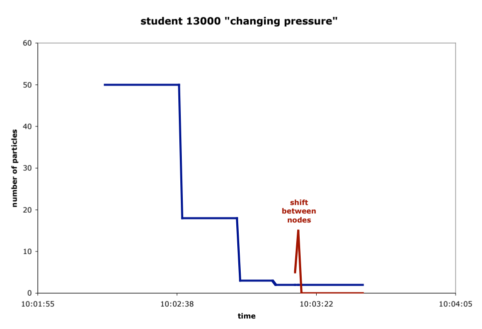
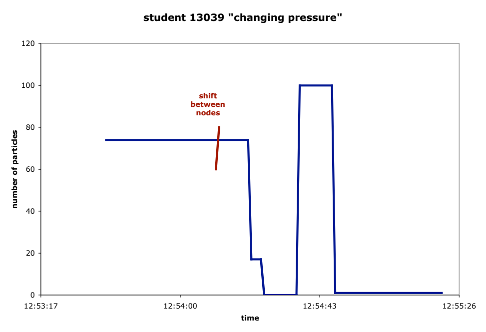
Pattern	Example	Additional characteristics
Straight to the point (2 students) The most informative state is accessed directly.		(1) Shorter overall observation time, but longer observation time per run (1) Longer time between actions (2) Fewer runs
Homing in (1 student) The most informative state is gradually approached through decreasing increments.		(1) Shorter overall observation time, and shorter observation time per run (2) Shorter time between actions (3) More runs
Oscillating (3 students) The model oscillates between two regimes, back and forth between high and low values.		(1) Longer overall observation time, but shorter observation time per run (2) Shorter time between actions (3) Intermediate number of runs

Figure 4: Patterns in exploring the "Changing pressure" model. Each graph relates to one student exploring the focal screens in the activity. X-axis denotes the real time. Y-axis denotes the number of particles. The red line marks the transition between the two screens. The default model setting is 50.

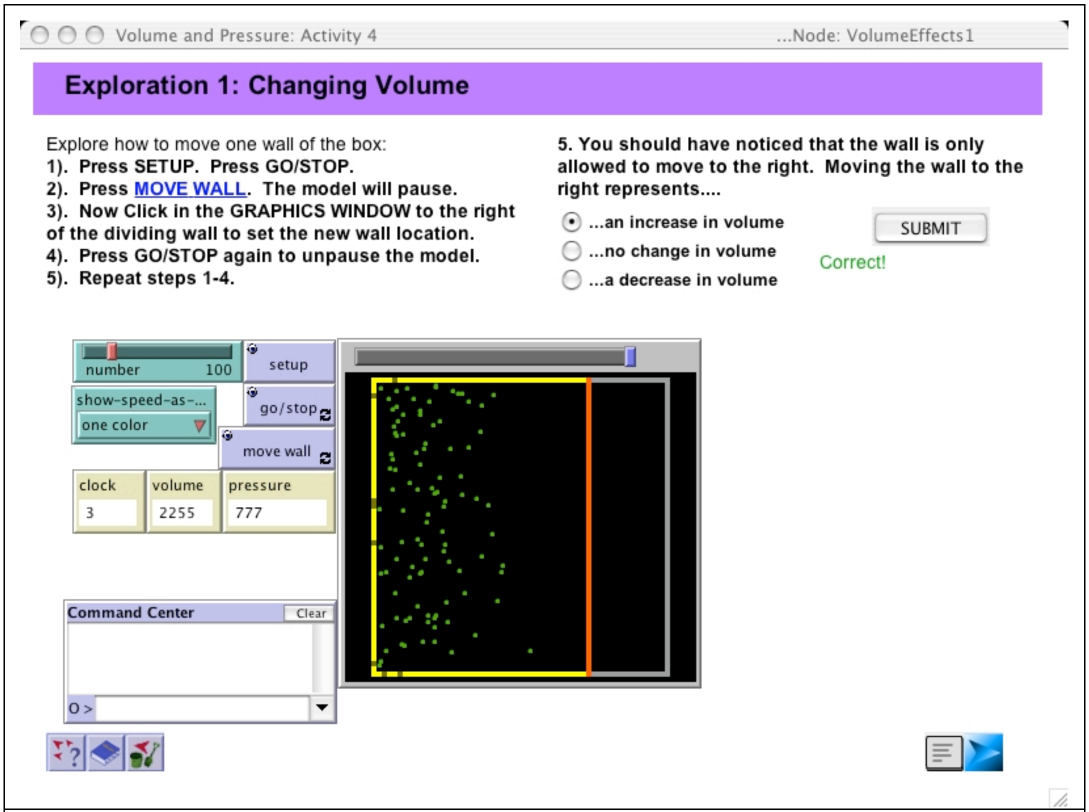
Study II: Patterns and goals

In this study we set out to compare the students' explorations in two activities, when the goals of the activities are structurally dissimilar. We compare students in two activities: when the goal is obtained by setting up the model in a *narrow part* of the parameter space; when the goal is obtained by using a *wide range of settings* in the parameter space.

The students are the same ones as those sampled in Study I. The first activity in the comparison is that from Study I: the students gravitate towards low particle numbers in the model, as that is the most informative range of settings. These model runs are compared with those in a later activity: the first section in "Volume and pressure" (see Figure 5). The students are asked to find out about the qualitative relationship between the volume of a container and the pressure exerted by the gas inside it. The students can change the volume of a container and observe the gas particles inside, as well as note the pressure on a "pressure versus time" graph and a pressure monitor. A number of guiding questions accompany the students' work: asking them to notice the volume, the density of the particles, the frequency at which the particles hit the wall, as well as the pressure. Additional questions ask for conclusions from these runs, regarding the qualitative relationship between volume and pressure, as well as density and pressure. Contrary to the first activity, students need to explore the model along a number of settings spanning a wide range of values to achieve the goal of this activity.

In the figure below (Figure 6), we present a comparison of the successive settings in the model runs in the two activities, each pair for the same student. Notice the similarities between the shapes of the graphs.

One name has been changed to reflect the common features in the explorations of the two activities: "homing in" was renamed "inching through space". This results from the common characteristic: relatively small increments are used to explore model's parameter space. "Homing in" reflected the convergence towards a specific value, which is not conserved in the second activity.



Exploration 1: Changing Volume

Explore how to move one wall of the box:

1). Press SETUP. Press GO/STOP.

2). Press MOVE WALL. The model will pause.

3). Now Click in the GRAPHICS WINDOW to the right of the dividing wall to set the new wall location.

4). Press GO/STOP again to unpause the model.

5). Repeat steps 1-4.

5. You should have noticed that the wall is only allowed to move to the right. Moving the wall to the right represents....

● **...an increase in volume**

○ **...no change in volume**

○ **...a decrease in volume**

Correct!

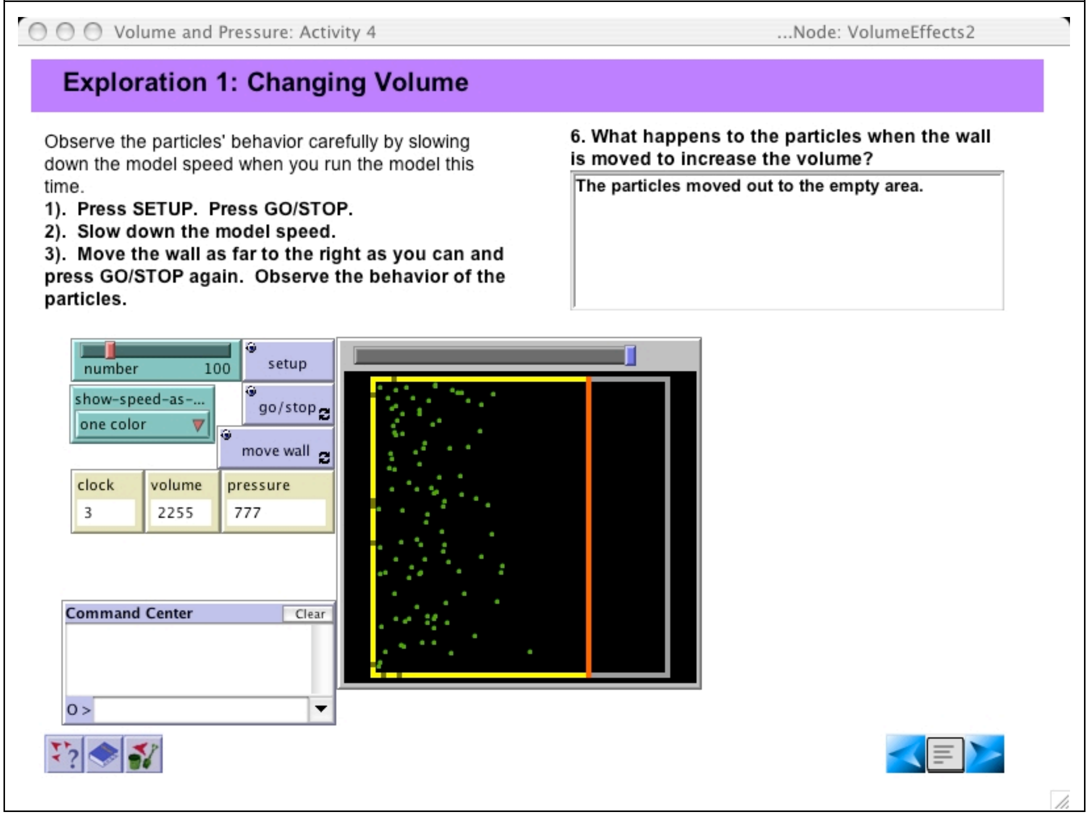
number 100

show-speed-as-... one color

clock 3

volume 2255

pressure 777



Exploration 1: Changing Volume

Observe the particles' behavior carefully by slowing down the model speed when you run the model this time.

1). Press SETUP. Press GO/STOP.

2). Slow down the model speed.

3). Move the wall as far to the right as you can and press GO/STOP again. Observe the behavior of the particles.

6. What happens to the particles when the wall is moved to increase the volume?

The particles moved out to the empty area.

number 100

show-speed-as-... one color

clock 3

volume 2255

pressure 777

Figure 5: "Volume pressure" activity screenshots.

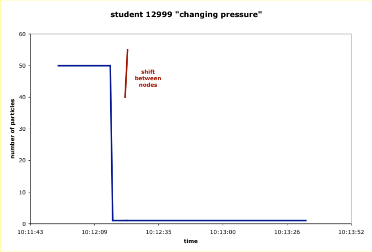
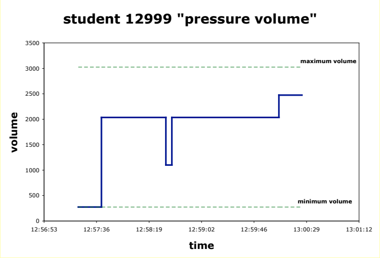
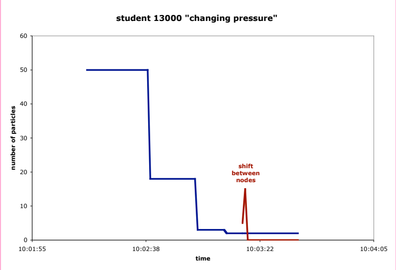
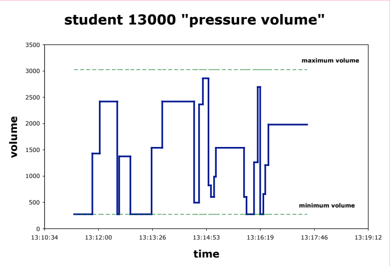
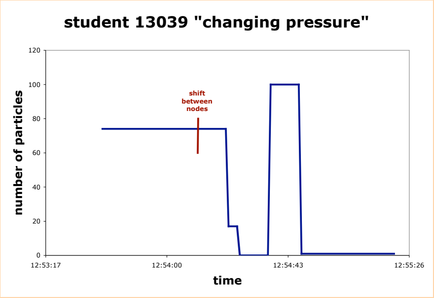
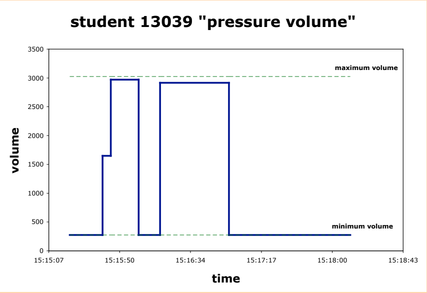
Pattern	Changing pressure	Volume & pressure
Straight to the point (2 students) Few key settings		
Inching through space (1 student) Incremental and extensive exploration		
Oscillating (1 student[1]) The parameter space is explored mainly via moving back and forth between extreme values		

Figure 6: Comparison of two model runs, in activities with different goals. The first run comes from "Changing pressure" with a distinct informative regime. The second run comes from "Volume and pressure" where a wide range of values is more informative. In both activities, X-axis denotes the real time. Y-axis denotes the number of particles in the first activity, the volume of the container in the second activity.

We can see one distinct difference between the two runs. While in the first activity the students directly or gradually reach a common narrow regime in the model's behavior space (low values for the number of particles), no such common regime is shared in the second activity.

Nevertheless, there are distinct similarities between the runs in the two activities. The students who employed a "straight to the point" strategy in the first activity still used a small number of runs in the second activity, employing a few key states. The student who "homed in" in decreasing intervals similarly employed many small intervals among successive runs. A student who oscillated between model behavior regimes displayed a similar pattern in both

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[1] One student did not do the second activity; one student encountered technical difficulties in operating the model.

activities

Thus, the main results from this study are threefold:

1. Students explore the models in characteristic way across tasks with different goals;
2. Model exploration when there are different goals is distinct in one aspect: when there is a particular goal state the students gravitate towards this state; when a range of values is informative, the students span a wider range of values;
3. The new results led to a generalization of the patterns in Study I to reflect goal-independent exploration patterns.

Study III: Patterns and tools

The third study examines the relationship between the model exploration patterns and the affordances of the available exploration tools. We focus on the two tools available for determining this model's settings: sliders versus NetLogo commands. In the previous studies, the students have used a slider to determine the settings in the model. The slider affords a *linear range* of values. In using NetLogo commands, the students are *unlimited* in the numbers that they can select in running the model[2]. Furthermore, using the command tools, students do not have to change the values linearly – they have "random" access and can select any value at any time. Thus, using NetLogo commands frees the user from the linearity of the slider. We examine whether the students employ this affordance.

In this study, we have focused on one exploration from the "Experimenting with particles" activity, in which the students choose one question out of six to explore the model and answer the question, or invent their own question. They then plan, conduct and summarize their investigation (see Figure 7). Earlier in the activity, the students learn how to use NetLogo commands to change the models. For example, they can use commands to change the particles' colors, have the particles leave a trace as they move and they can select the speed of the particles.

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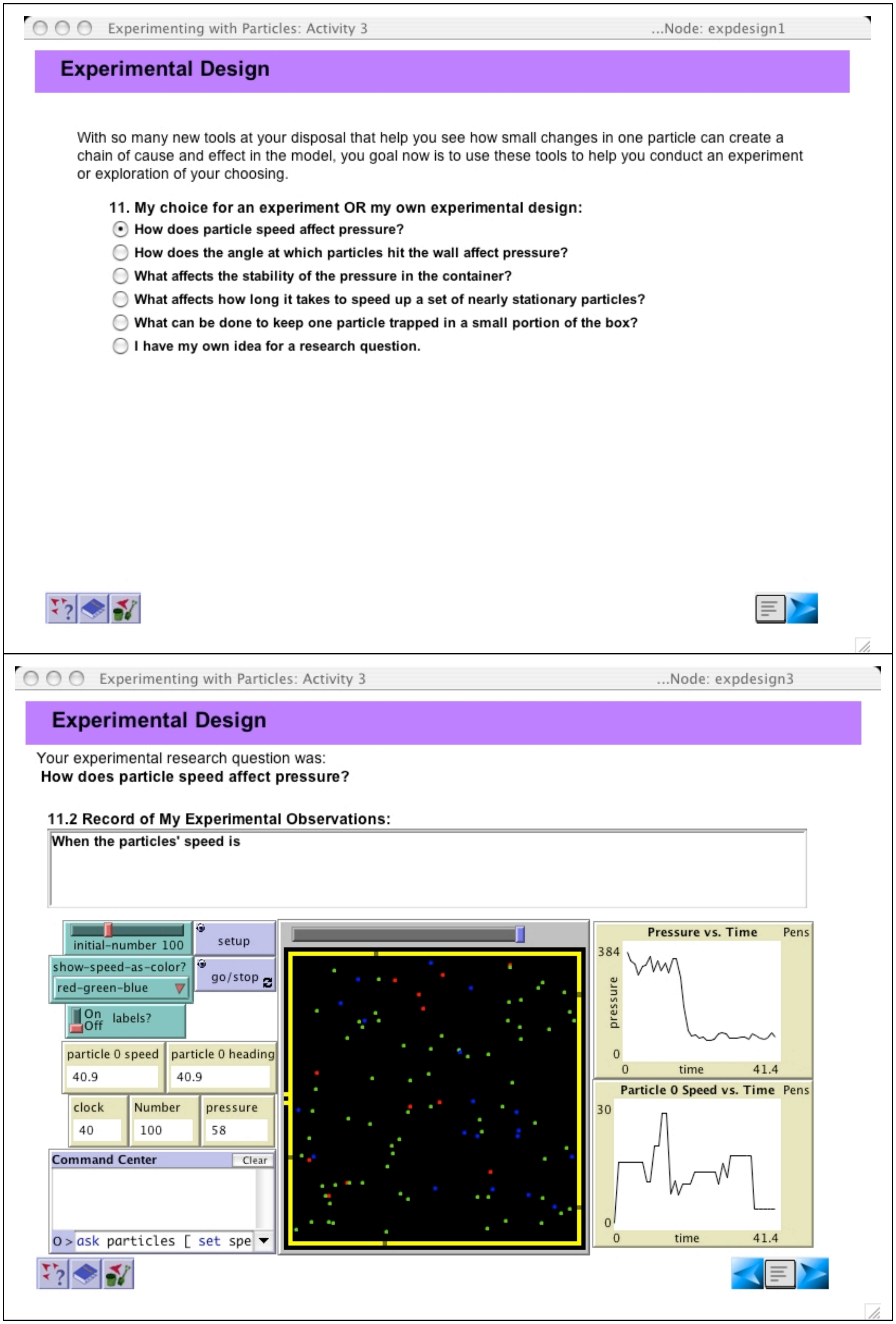
[2] Computer's representations of numbers may limit the effective range of these value, although in practice, it is unlimited for most purposes.



Experimenting with Particles: Activity 3 ...Node: expdesign1

Experimental Design

With so many new tools at your disposal that help you see how small changes in one particle can create a chain of cause and effect in the model, you goal now is to use these tools to help you conduct an experiment or exploration of your choosing.

11. My choice for an experiment OR my own experimental design:

● **How does particle speed affect pressure?**
○ **How does the angle at which particles hit the wall affect pressure?**
○ **What affects the stability of the pressure in the container?**
○ **What affects how long it takes to speed up a set of nearly stationary particles?**
○ **What can be done to keep one particle trapped in a small portion of the box?**
○ **I have my own idea for a research question.**

Experimenting with Particles: Activity 3 ...Node: expdesign3

Experimental Design

Your experimental research question was:
How does particle speed affect pressure?

11.2 Record of My Experimental Observations:

When the particles' speed is

initial-number 100
show-speed-as-color? red-green-blue
labels? On Off
particle 0 speed 40.9
particle 0 heading 40.9
clock 40
Number 100
pressure 58

Command Center

```
O> ask particles [ set spe
```

Figure 7: “Experimenting with particles” focal screens.

We have examined the logs of 30 students who had all selected the same question: “How does particle speed affect pressure?” The following graphs (Figure 8) display the students’ exploration patterns. Note that in the third pattern, we had to shift to a logarithmic Y-axis scale, as the students were changing orders of magnitude for the particles’ speed.

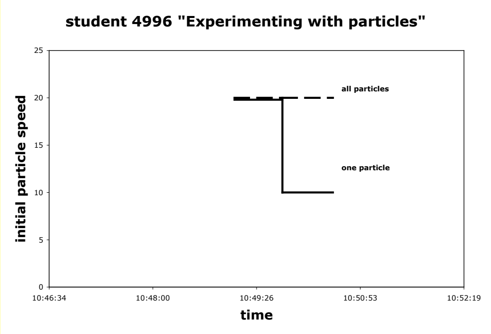
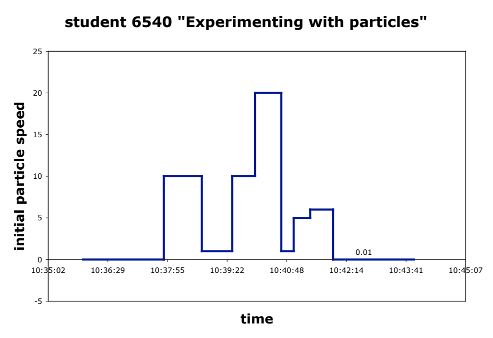
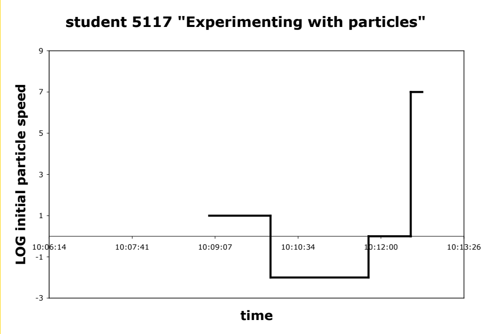
Pattern	Example
Straight to the point (6 students, 20%)	 student 4996 "Experimenting with particles"
Oscillating (within a linear range) (5 students, 16%)	 student 6540 "Experimenting with particles"
Oscillating EXTREME (moving among orders of magnitude) (16 students, 53%)	 student 5117 "Experimenting with particles"
Did not explore the model (3 students, 10%)	

Figure 8: “Experimenting with particles” successive settings in a model, testing the effect of the gas particles’ initial speed on the pressure in the container. X-axis is the real time. Y-axis is the initial speed (logarithm of in the third pattern). N=30.

Among the three patterns we have described so far, only two are observed in this model. By far, the dominant pattern is that oscillating between higher and lower values for the particles' speed.

Of note is the way 16 out of the 30 students utilized the affordances of NetLogo commands by setting their oscillations to values along orders of magnitude, rather than within a linear range. For example, one student in the example above (Figure 8) used the following sequence for the particles' speed: 10, 0.01, 1, 9,999,999. Due to the extreme jumps we have named this variant "oscillating EXTREME".

To conclude this study:

(1) When varying a setting via textual NetLogo commands, rather than through a linear slider, half the students oscillated back and forth across orders of magnitude, rather than the more limited space offered via a slider. The greater freedom this tool offers afforded their exploration along a greater range in the model's behavior space. Not only did they explore a larger range, the sequence of values was not linear.

(2) The dominant pattern in this exploration is an oscillating sequence of values.

Study IV: Patterns and goals (Part B), Mathematical underpinnings

So far, we have looked into the students' model exploration patterns when the goals involved qualitative features and relationships. The goals were either focused on a particular range of parameters, or upon a general qualitative relationship. In this study, the exploration patterns are examined when another type of *goal* is presented: *deriving a quantitative relationship*. In contrast to the previously described activities, in this activity the students use a table to record their data. Recording the data in this way provides a trace of previous model runs. Moreover, we compare the students' explorations when the underlying mathematical functions are distinct: a linear versus an inverse function that describes the macroscopic relationships.

We portray the model exploration of 35 students, as they collect data aimed at deriving a relationship between macroscopic variables of gases: the number of particles (N) and the pressure they exert (P) in a fixed-volume container with a constant temperature; the volume (V) of the container and the pressure inside it (P), when the number of particles and the temperature are constant. The first relationship is linear: As the number of particles is increased, the pressure goes up ($P = constant * N$); the second relationship is an inverse: as the volume grows, the pressure goes down (Boyle's Law: $P * V = constant$). While variation by constant intervals would be a fruitful strategy for exploring the model when a linear relationship underlies its behavior, the same is not true for an inverse relationship. In an inverse relationship, using constant intervals for the independent variable produces many values in a range, where the changes are relatively small. Achieving a good spread of points involves increasing the increments along the range, so that a higher density of data-points result in the part where the system's behavior changes more rapidly.

Before this portion of the activity, the students have explored the relationships qualitatively. After this exploration, they obtain a scatter-plot of their data and derive the quantitative equation relating the variables.

The goal is stated explicitly: deriving a quantitative relationship from this data. A table is used to organize the data in 5 pairs (see Figure 9). This representation is a record and reminder of previous model runs, providing data for the following screens. The model is designed to allow only one way for the independent variable (N, V) to be changed. The values can only be increased; cannot be decreased[3].

In the first activity, a constant addition of particles is encouraged by the tools in the model: when adding particles into the container, the students set the amount of particles to add and then press an appropriate “add particles” button. Thus, repeated clicking on this button produces a linear sequence of N values.

However, in the second activity, such scaffolding is not offered. When increasing the volume of the container, the student stops the model; clicks on the box to determine the new location of the wall, and then runs the model again. Any location for the wall can be used within the range between the smallest and the largest box. The only limitation is that they need to fit five values within this range, so that the table will get filled.

For each student, we have examined the two model runs. We present the exploration patterns separately for each model in Figure 10 and Table 1. N = 35.

In the first activity, the model is organized to encourage a constant increase in N, the independent variable. We have seen that in this activity, almost all of the students employed the externally-structured sequence of constant addition of particles. We name this strategy “constant intervals”. This is another strategy we have added to our host of strategies in the open exploration mode. It shows up when structured by the activity aimed at obtaining a quantitative relationship and constrained by the model affordances. However, we note one diversion from the use of default settings: Among the 21 students who used the “constant intervals” strategy, only four used the model’s default settings (50 particles initially, 50 particles added at each button press). The others changed the number of initial particles and the number of particles to be added, before embarking on their model run. Even within a relatively constrained setting, the students employed the exploratory affordances, thus individuating their investigation.

In the second activity, “Volume and pressure”, the sequence of settings is less constrained. To determine the volume, they do not enter numerical values. The students click on the box to decide upon the next location of the wall. We have seen the following distribution of strategies among the students. Rather than using mainly constant intervals, as in the “number and pressure” exploration, we can see a wider distribution. The majority (38%) adapted to the inverse relationship exhibited in the model behavior, using increasing increments, that capture the faster change in the lower regime for volume.

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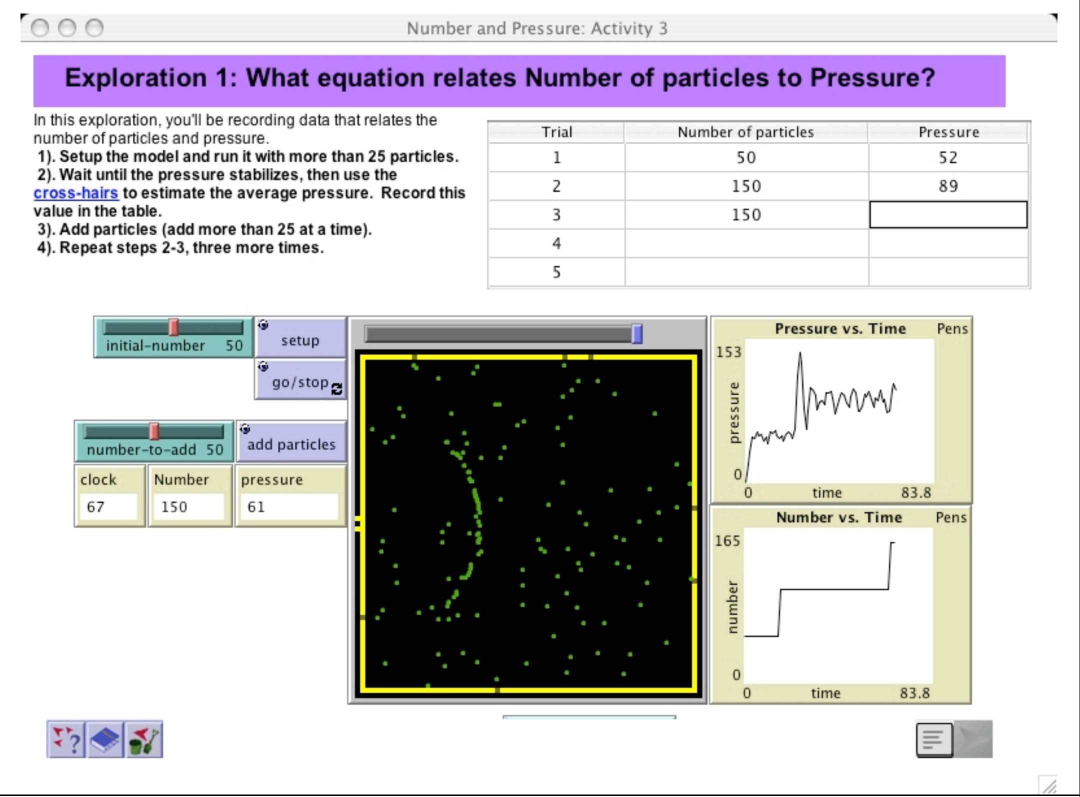
[3] We have removed this limitation in a later version of the curriculum, to enable greater flexibility in the students’ explorations.



Exploration 1: What equation relates Number of particles to Pressure?

In this exploration, you'll be recording data that relates the number of particles and pressure.

1). Setup the model and run it with more than 25 particles.
2). Wait until the pressure stabilizes, then use the cross-hairs to estimate the average pressure. Record this value in the table.
3). Add particles (add more than 25 at a time).
4). Repeat steps 2-3, three more times.

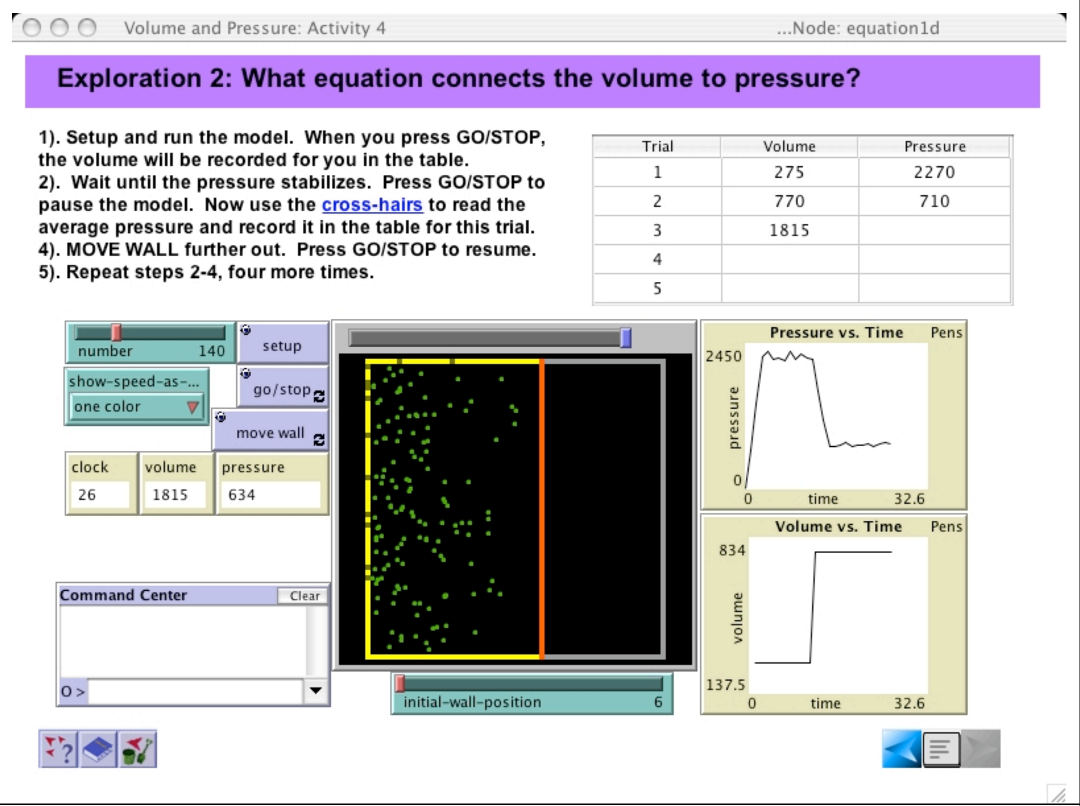
Trial	Number of particles	Pressure
1	50	52
2	150	89
3	150	
4		
5		

clock 67

Number 150

pressure 61

Number & Pressure exploration screen



Exploration 2: What equation connects the volume to pressure?

1). Setup and run the model. When you press GO/STOP, the volume will be recorded for you in the table.
2). Wait until the pressure stabilizes. Press GO/STOP to pause the model. Now use the cross-hairs to read the average pressure and record it in the table for this trial.
4). MOVE WALL further out. Press GO/STOP to resume.
5). Repeat steps 2-4, four more times.

Trial	Volume	Pressure
1	275	2270
2	770	710
3	1815	
4		
5		

clock 26

volume 1815

pressure 634

Pressure & Volume exploration screen

Figure 9: "Number and pressure", "Volume and pressure" quantitative exploration screens.

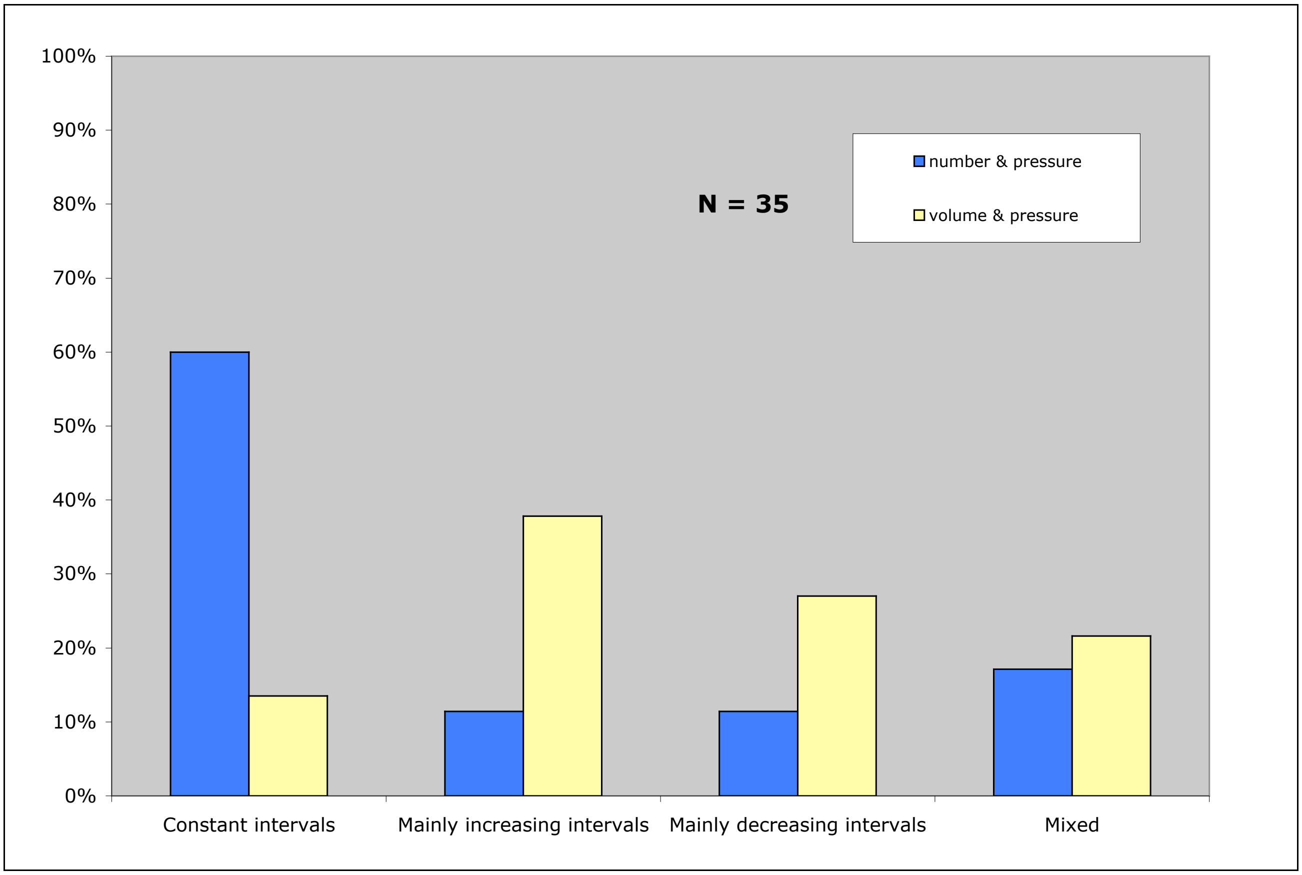


Figure 10: Exploration patterns in a structured activity aimed at deriving a quantitative relationship. Comparison of variation patterns in two activities: Number of particles and pressure (NP) and volume and pressure (VP).

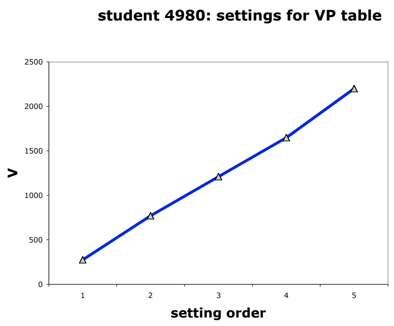
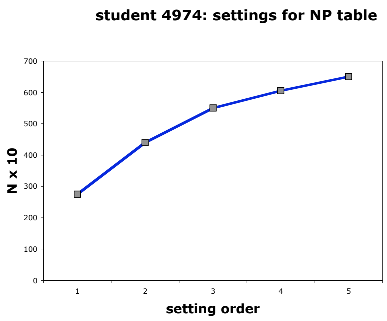
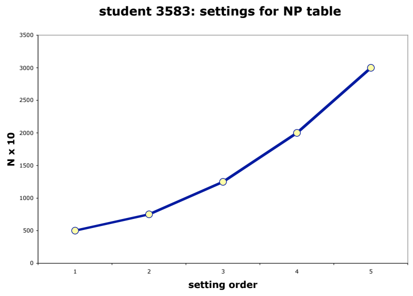
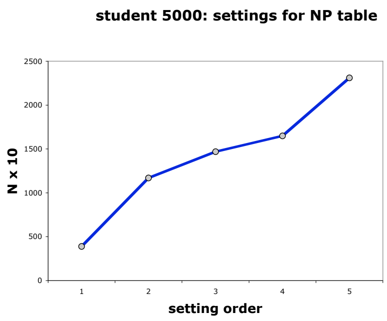
Pattern	Example	Number & Pressure	Volume & Pressure
Constant intervals		60%	14%
Mainly decreasing intervals		11%	27%
Mainly increasing intervals		11%	38%
Mixed		17%	22%

Table 1: Exploration patterns in a structured activity aimed at deriving a quantitative relationship. Comparison of variation patterns in two activities: Number of particles and pressure (NP) and volume and pressure (VP). N=35.

To summarize this study, we have seen the following:

1. In an activity aimed at deriving a quantitative relationship, some of the students employed a new strategy: “constant intervals”, where the independent variable in the experiment is increased at constant intervals. This pattern was not seen in the three open activities, aimed at qualitative relationships in Studies I, II, III.
2. In a highly scaffolded model with a linear function underlying the model’s behavior, almost all the students used the “constant intervals” strategy. However, even then, a large portion of the students used alternative strategies.
3. In a less scaffolded model with an inverse function underlying the model’s behavior, almost half of the *students adapted their exploration to the inverse function* and a wider distribution of strategies was observed.

Study V: Individual pathways – Student number 4981

In this section, we illustrate the path of one student through the curriculum, highlighting the student’s typical and atypical manipulation of the models. From describing the pre-test and post-test results for this student, we delve into the activities and attempt to understand some of the observed shifts.

Student number 4981 was selected randomly out of a large pool of data. We do know that she is a 9th grade female from a medium-sized high-school, with a highly diverse population, speaking 16 languages apart from English.

When observing her pre-test and post-test answers we note the following.

Walking in, this student is quite knowledgeable regarding several aspects of gas behavior: She has a correct mental image of the gas particles’ spatial distribution and she knows the canonical definition of pressure. Regarding the various relationships among the aggregate gas variables, we observe that qualitatively – she had a good grasp of these relationships; however, quantitatively, she can solve correctly only for Boyle’s Law. Her ability to reason with graphs, which depict a physical situation, is limited as well. Regarding gas particles’ behaviors, she is not as knowledgeable – with relation to the KMT (Kinetic Molecular Theory) assumptions, changes in particles’ direction and speed upon collision, as well as assuming that particles have intentions in moving into a vacuum.

In the post-test, we can see some regions of improvement. Student 4981 improved regarding her understanding of KMT and the individual particle behaviors (collisions with other particles, with a surface) and in the quantitative aspects of problem-solving in the domain: understanding and implementing the relationship between aggregate system properties (the gas laws’ equations), interpreting the graph representation of their temporal changes and deriving an equation from a graph. However, she still assumes that particles have intentions, and has difficulties relating micro-particle-behaviors to aggregate properties of the system.

What happened between the pre-test and the post-test? We base the following on the logs of her answers to the many questions in the script and from the way she manipulates the models.

This student quickly grasps the tools and representations, and has only few problems in manipulating the models. We have not observed any typical errors students had made in manipulating the models, which resulted from not following through the accompanying instructions[4].

In each of the seven activities' post-assessment, she is completely successful. Thus, within the activities, we can see greater learning gains that are not necessarily evident in the post-test results. In the activities, she can tie the micro-to-macro relations, in a way that was not seen a few days later in the post-test. We will highlight this aspect of her learning.

We note that overall, Student 4981 does not explore the models beyond the tasks' minimum requirements. She uses the models in a perfunctory fashion, according to the scripts' suggestions and no more. For example, when the script suggests that she change the number of particles in the container and observe the resultant pressure, she does this - but only once. We have seen other students employ several settings in the very same activity. In the activities geared at deriving an equation (see Study IV), we have seen her use mainly a "constant intervals" pattern of exploration (See Figure 11). This, together with the pre-test results and her carefully following the scripts' instructions demonstrate that this student is a good students, well-adapted to the class-room environment.

In most cases, we do not see any playful investigations or inventive patterns of exploration. Thus, it is interesting to note when she departs from this pattern. This happened in two instances.

In the second activity "Changing pressure", she investigates "When is pressure zero?" (for details, see Study I) for a duration of 2:13 minutes. This activity targets the more minute interpretation of pressure at a micro-to-macro approach, highlighting the distinction among three-dimensional collisions and the two-dimensional wall-hits; as well, as the role of measurement in determining pressure. We can see the sequence of settings she employs for the number of particles in the box in Figure 12: 50, 53, 69, 36, 4, 1. She starts out with the default value of 50 particles, gradually increasing the value to 69 particles. After this, she begins to "slide" down to a low value for this number, in a pattern we have called "homing in". The intervals among settings become smaller and smaller, as the target region is approached, ending with a single particle in the box. We can interpret this sequence in the following way. Initially, she increases the number of particles twice, possibly reflecting an alternate understanding of the system, or having no clear idea of which way to go with the exploration. However, observing the resultant

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[4] An example of a typical error is changing initial variables after the model has started running. We have addressed such problems by adding several short intervening activities to scaffold the students' manipulation of the models.

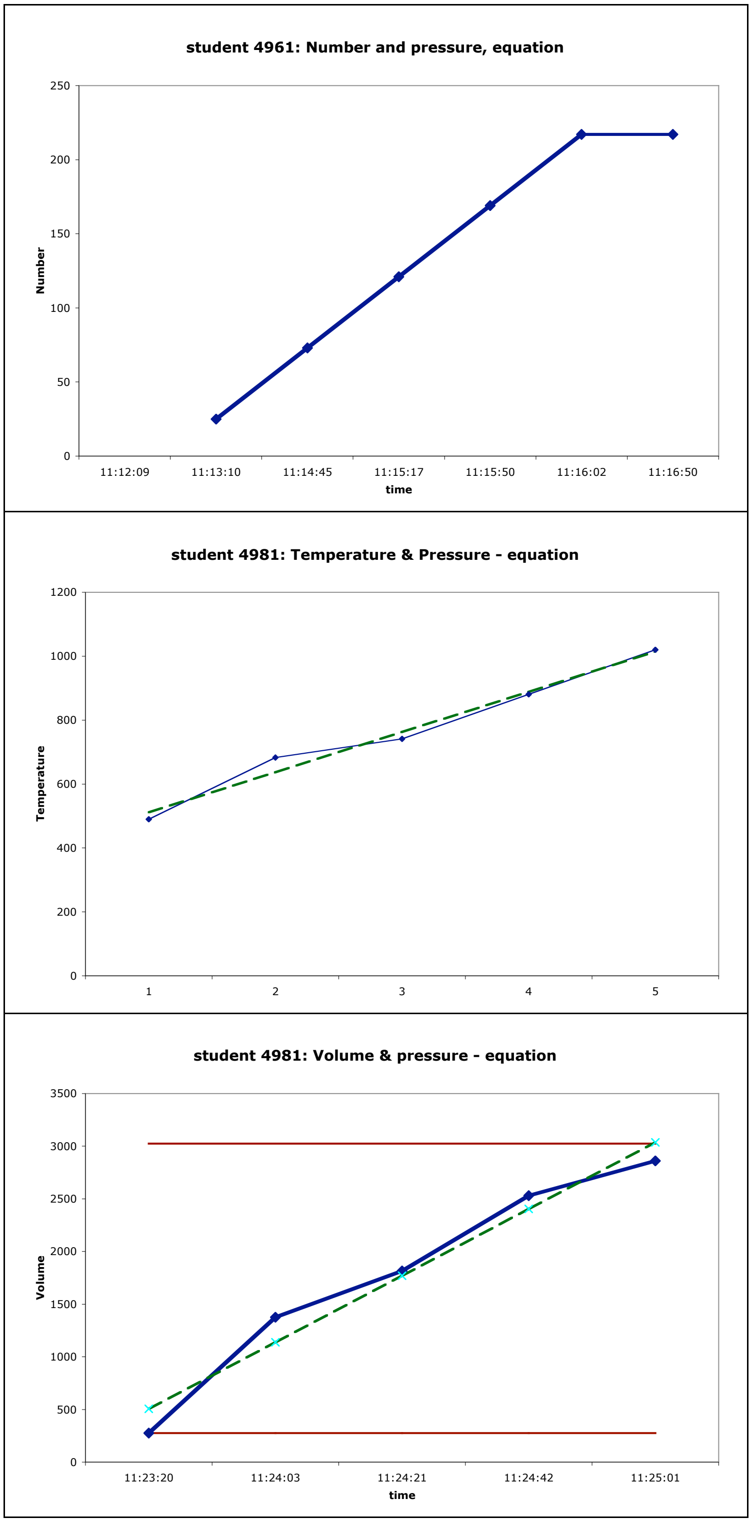


Figure 11: Student 4981's explorations of the models, geared at deriving an equation relating aggregate variables for the behavior of a gas. The green dotted line represents the closest fit of a "constant intervals" pattern. For the "Volume & Pressure" exploration, a 5% deviation from the fitted function is still considered "constant intervals" since the change in volume is made via clicking on the model, rather than changing a variable slider.

pressure clues her into a fruitful path of investigation: go down. She reduces the number of particles, but not enough – the pressure is lower, but never zero. Two jumps down, and she has reached the regime where the pressure is *sometimes* zero – four particles and then one. With such a small number of particles in the box, the pressure is mainly zero – fluctuating up when the particles hit the container's walls. We note two important points. This activity targets a connection between individual particle behaviors and the aggregate system properties, an aspect she has not demonstrated an understanding for – in the pre-test or the post-test. This invites an intense exploration, examining the system along an intermediate range of regimes, carefully reaching a situation where this connection is clarified. Once this is settled, the exploration ends. We also have data on other features of the way she manipulates the model: The model was actually running during 1:13 minutes, or an average of 0:12 per run, a short duration with respect to other students (see Appendix I). She has performed 22 actions upon the model, an average of 6 seconds between actions. This is relatively fast – demonstrating a "click-happy" investigation, quite distinct from her other explorations. To summarize this activity, the student has shifted from a minimal yet planful style of exploration to another strategy "homing in" or "inching through space". This happened following a good question and subsequent confusion.

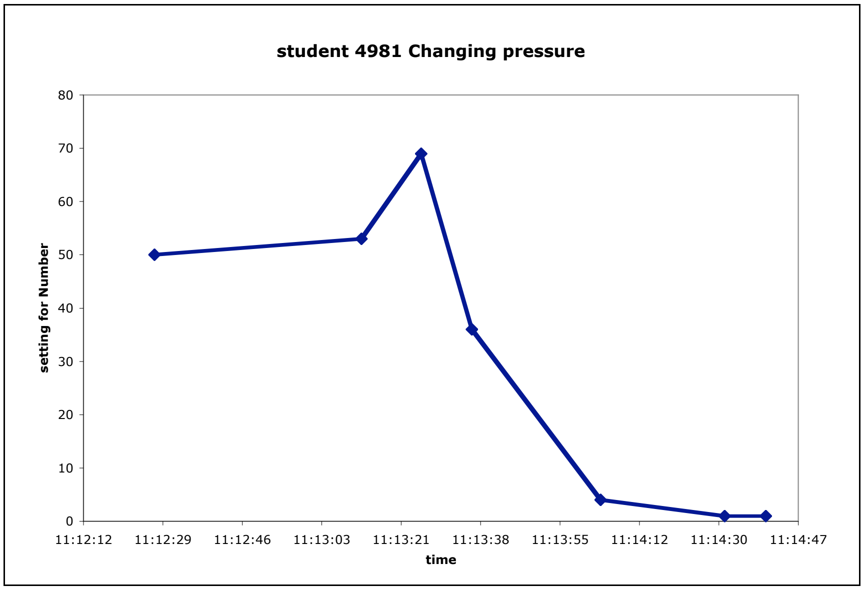
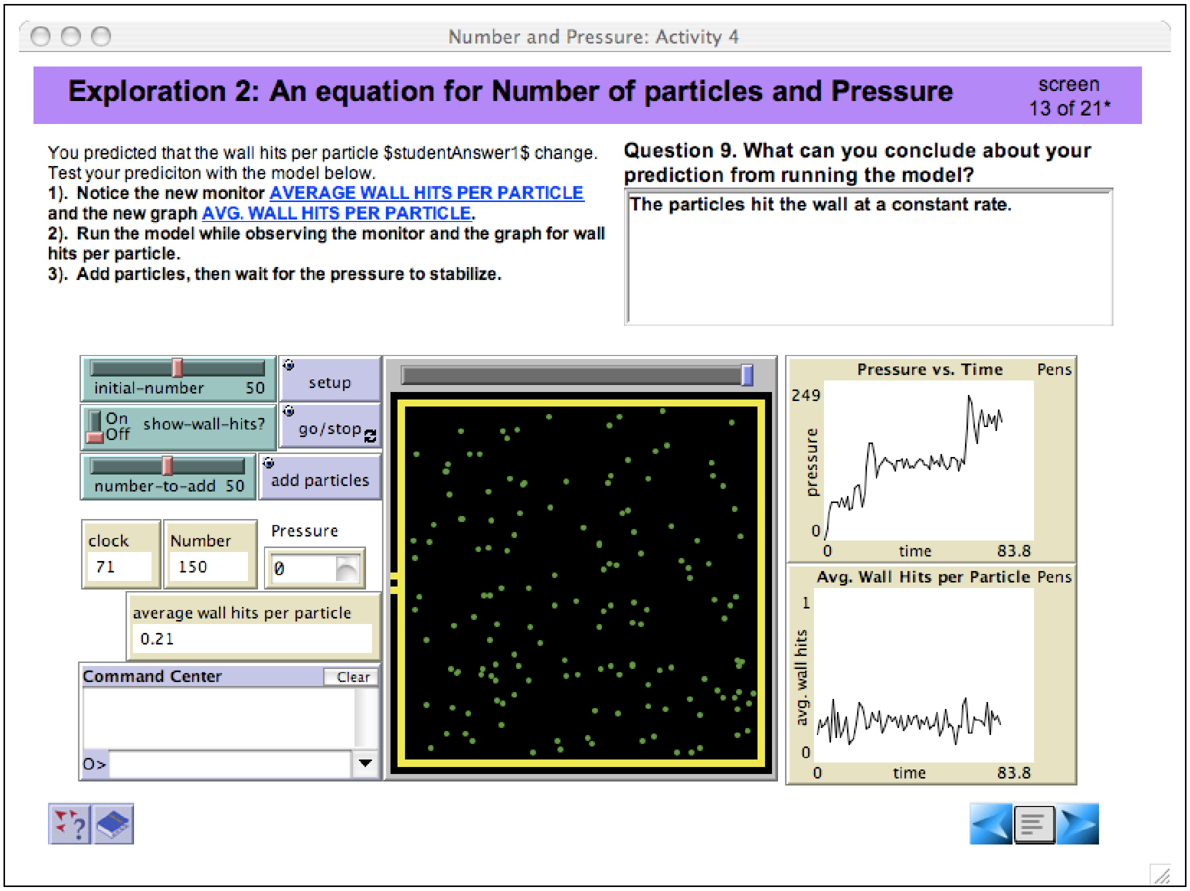


Figure 12: Student 4981's exploration of "When is the pressure zero?" in the "Changing pressure" activity.

Another puzzle is posed in the fourth activity "Number and pressure". While the pressure increases linearly with the number of particles in a container, the average rate at which a *single* particle hits the wall remains *constant*. This is another case in which we highlight the distinction among the micro and macro levels of description in the system (see Figure 13). In predicting what will happen before testing this out in the model, she has predicted: "By rate as they hit the wall mean the force they exert on it? Or does this mean the rate (how often) each individual particle hits the wall? I'm not sure about the question. But I think that it will increase, although I do not know the rate." We can see her confusion regarding this question, is it forces they exert? Or rate of hitting the wall?: "I'm not sure about the question". As most students, she finally predicts that the rate will increase. Her forthcoming exploration is highly intensive (see Figure 14). Twenty settings are employed during almost two minutes of exploration. Once again she has turned to an "inching through space" strategy of exploration. The puzzle elicits a very different style of manipulating the model – closely spaced multiple settings, as a wide range of the parameter space is employed. We note the similarity in strategies with the previous exploration, and their distinction from the perfunctory investigations in the rest of the curriculum. In answering the question immediately following the exploration, she types (the scripts' question are bolded): [**What can you conclude about your prediction from running the model?]** "From this model, it doesn[']t seem to matter how many particles there are. The average number of wall hits per particle is still around the same." [**The average number of wall hits per particle does not change significantly with more particles. Why?]** "I think that no matter how many particles there are, each particle still has the opportunity to collide with the wall. I do not think density with the wall matters." She has ended at a very different place from which she had started. She had started with a merged view of description levels – "if the aggregate rate at which particles hit the wall increases, so does the individual rate for each particle". She ended with a distinction among the micro- and macro-levels, describing the system.



Exploration 2: An equation for Number of particles and Pressure

screen
13 of 21*

You predicted that the wall hits per particle $studentAnswer1$ change. Test your prediciton with the model below.

1). Notice the new monitor AVERAGE WALL HITS PER PARTICLE and the new graph AVG. WALL HITS PER PARTICLE.

2). Run the model while observing the monitor and the graph for wall hits per particle.

3). Add particles, then wait for the pressure to stabilize.

Question 9. What can you conclude about your prediction from running the model?

The particles hit the wall at a constant rate.

initial-number 50

show-wall-hits? Off

number-to-add 50

clock 71

Number 150

Pressure 0

average wall hits per particle 0.21

Figure 13: Screenshot of activity highlighting the distinction among the increase in pressure and the constant rate at which each particle hits the wall ini the “Number and pressure” activity.

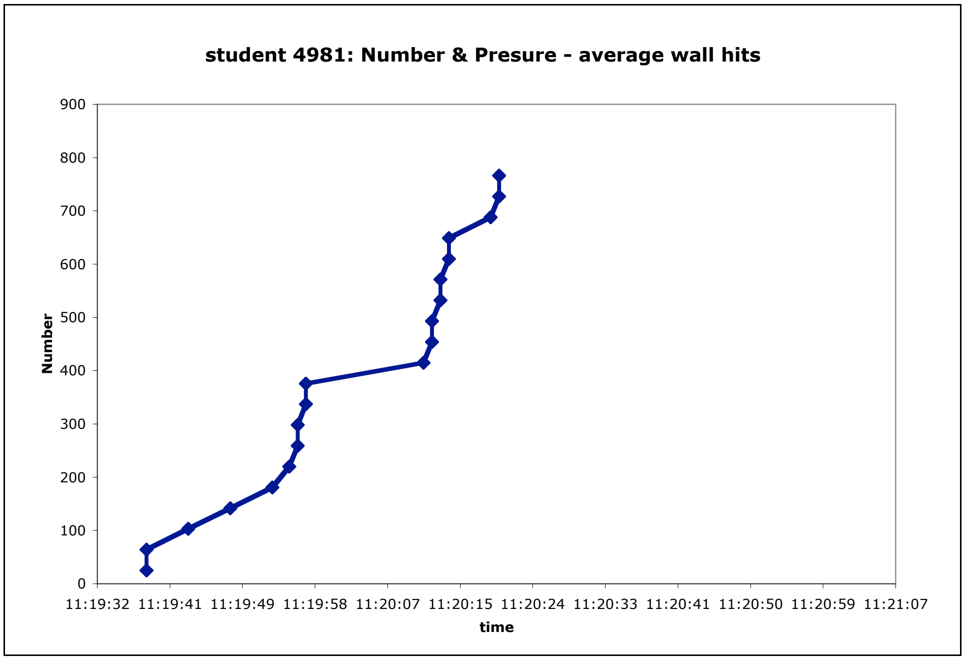


Figure 14: Student 4981’s exploration of the activity highlighting the distinction among the increase in pressure and the constant rate at which each particle hits the wall ini the “Number and pressure” activity.

Unfortunately, this emerging understanding of gas behaviors did not extend into Student 4981's post-test, the way we typically measure learning at school. While she had shown several learning gains in other important dimensions, the micro-to-macro connections were not sustained.

However, here the power of logging and the subsequent teacher reports play an important role. Based on the logs, we are developing a teachers' report, which would highlight these very styles of model exploration. A teacher may observe a change in model exploration style that reflects puzzles, curiosity and surprises. At then end of the day, reflecting on this kind of information, the teacher can choose to intervene. Fragile emerging knowledge can be elicited, communicated and strengthened through the ensuing conversations in the classroom.

DISCUSSION

How do students search for information within computer models? We have found that activity goals, available tools, underlying model behaviors and personal styles interact in shaping the particular form by which information is searched for. These forms are described via a multi-faceted framework (Figure 2), which incorporates perceptual learning, motor actions, problem solving and domain-specific features. This framework is situated within a wider structure that seeks the relationships between prior knowledge, learning paths through interaction with computer models and learning outcomes. In this paper, we focus upon the students' activity with the models.

We have conducted four studies, varying the goals of the activities, the exploration tools' affordances and the underlying mathematical relationships; while examining the model exploration patterns. In analyzing these patterns, we have centered mainly upon the sequence of settings the student employs in running the models; but include observation times, average time-per-action and the richness by which the parameter space is explored. This information was obtained from intensive logging of the students' actions with the models, and the models' resultant behaviors and states.

Our investigation was guided by four goals:

(a) Characterizing students' model exploration.

(b) Describing how these patterns may change when the goals are varied.

(c) Analyzing the impact of different tool's affordances on the students' exploration patterns.

(d) Comparing students' exploration of the model's parameter space, when different mathematical relationships underlie the target system's behavior.

PATTERNS IN EXPLORING MODELS

In our research to date, we have detected four exploration patterns: “straight to the point”, “inching through space”, “oscillation” and “constant intervals”. The first three were found in more free-form activities, when qualitative relationships and properties were sought after. The fourth pattern was found in more constrained activities, when the students were in the process of deriving quantitative relationships. Additional features of the exploration typified these patterns. We shortly discuss each pattern in turn.

STRAIGHT TO THE POINT

This exploration pattern employs few key settings, and is characterized by greater deliberation before action, longer observation durations per run, and a less dense testing of the parameter space.

This pattern describes planfulness operating in a terse efficient mode. Few settings are used, but the resulting model behavior is carefully observed. Meticulous and observant, students operating in this efficient mode are using the model in a way, which may afford a deeper understanding of each regime. However, they may miss critical settings or transitions among regimes, which can be discovered through a richer sampling of the parameter space.

INCHING THROUGH SPACE

This exploration strategy gradually moves through space, testing several settings, closer and farther apart. It is also typified by less deliberation before action, shorter observation times and a rich dense testing of the parameter space.

One may call this strategy “click-happy”. We are reminded of people moving swiftly through virtual spaces in adventure gaming situations. Quick observation is followed by speedy action as the predator is avoided and the swinging golden coins are captured and pocketed. It may seem that very little is gleaned from such speedy model changes and short observations. However, while breaking with traditional learning patterns, it may well be true that a person well-adapted to such environments may be able to detect and generalize complex sets of information quickly. The speediness of the scan may be compensated for by the many touches upon variants in the model’s behavior. The richness in exploring the parameter space may be conducive to noticing critical settings, when the model departs from one behavioral regime to the next. We have seen in Study V that one student shifted to this pattern when puzzles regarding micro-to-macro relationships emerged in the activity. Intensive yet swift exploration resulted in an increased understanding of this complex system.

OSCILLATING

“Oscillating” describes a strategy which moves back and forth between extreme values in the parameter space: up, down and up again. Density of settings within this space is an intermediate between the previous two patterns; overall observation time is longer, but shorter per run; actions are spaced by relatively short intervals.

This most common strategy has provokes interesting questions. In moving between extremes, it seems that a continual comparison is made between “now” and “previous”. As a model’s settings change, the previous model behavior soon disappears and leaves no trace or record. If one were to search for a relationship between such changes and the resultant model behavior, pair-wise comparison between the current and the last setting emerge into an oscillating pattern, which is guided by the edges of the parameter space.

CONSTANT INTERVALS

The “Constant intervals” pattern was observed when the students were recording data in a table to be used in the next screen in order to derive an equation. It is described as a constant change to either the independent or dependent variable in the experiment, e.g. 10, 15, 20, 25... The models were planned (in slightly varying degrees) to structure and scaffold such sampling, although the students are free to depart from structured scheme. A linear addition to the independent variable is the most commonly taught strategy in science classes. Constant additions to the dependent variable may seem quite wrong, as this runs contrary to normal science inquiry teaching. However, when the underlying functions are not linear, as in Boyle’s Law, if one wishes to study the changes in the system behavior – it would make more sense to sample evenly for the dependent variable, rather than independent variable. This way, one captures the full range of change in the underlying behavior.

THESE PATTERNS ARE CONSISTENT, YET IMPACTED BY GOALS

Are these patterns context- and goal- dependent, or do they reflect some personal style in search for information?

We have found that the answer is mixed. On one hand, when shifting from goals that involve qualitative relationships to goals that involve quantitative relationships, the exploration strategies changed in kind. However, within the qualitative explorations, which are structured by different goals, some features of the exploration remained consistent. The main form of the pattern – few key settings, small increments or oscillation between extremes remained constant. They differed by whether they spanned a wide range or converged upon a small range, which relates to their particular goal structure.

Thus, the resolution at which these patterns are described seems to have been the right grain to detect both personal stamps and variants, as an individual adapts her search to different goals. Different goal structures invite different types of exploration; however, personal ways of engaging with computer model spaces have a large impact on these types as well.

TOOL AFFORDANCES AND EXPLORATION PATTERNS or “OSCILLATION EXTREME”

Learning commands in languages such as NetLogo requires a higher investment than merely learning how to manipulate the model’s widgets: sliders, buttons and switches. Is it worth the trouble? Previous work (e.g., Wilensky & Reisman, 1998; Wilensky, 1999b) has demonstrated that by constructing models, students form deep understandings of the target domain. However, in this study only a very limited form of construction is available to the student. The model has been constructed by others and the changes that the student affect via programming commands relates to more superficial properties and visualization tools, and not to the underlying model rules. Nevertheless, using these commands may free the students from constraints inherent in the widgets, such as the linearity of the sliders' range of values.

We have found that once using such commands, half the students freed themselves from linear exploration and explored the parameter space, by changing orders of magnitude in a variant of a pattern we have called "oscillation extreme". This is an interesting result, as it suggests that understanding ones' tools and exploiting their affordances is an important aspect of more sophisticated technology use. Moreover, it suggests that the understanding that there are multiple tools that afford activity within these domains, rather than viewing them as "givens", is an important component of modeling literacy in particular, and perhaps more generally in computer literacy.

From the perspective of complex systems, we find that spanning orders of magnitude rather than systematic constant variation is a fruitful strategy in reaching deeper understanding. In relating the moon to the solar system to the galaxy, we reach a more comprehensive understanding of the system, as it behaves differently at different scales.

UNDERLYING MATHEMATICAL RELATIONSHIPS

How does the model's underlying mathematical function affect the students' exploration patterns? Do they use the commonly taught "constant additions" for the independent variable regardless of the rate of change of the dependent variable? As described above, commonly taught practices in science inquiry do not always fit for every context. If one didn't know the relationship between the variables, linear variation of the independent variable is a good heuristic for mapping out the space. However, this is not the case in our investigation. Prior to this quantitative section, the students have interacted with the model and attended to its qualitative relationships and properties. If the students have internalized the inverse relationship between volume and pressure in Boyle's Law, they may notice that the pressure changes faster when the volumes are smaller. In this case, evenly spacing the values for the dependent variable, rather than the independent variable will give a better sense of the full parameter space.

We have found that more than half the students adapted their exploration to the inverse function underpinning our "Volume and Pressure" model. They either consistently increased the increment size or hybridized a linear strategy, "breaking the slope" at some point to increase the increments. We were quite taken with the results. Inverse relationships are typically harder to learn, and we have a "linear" bias in our spontaneous view of the world (Nemirovsky, 1994). However, in this case we have seen the students internalize the inverse relationship, even without numerical and symbolic forms, simply via model manipulation and observation. This internalization is evidenced in their adaptation to the specifics of the function.

RESERVATIONS

While the Modeling Across the Curriculum project currently has thousands of students' activity logs, this is not evident in our analysis. As we are still in the initial stages of our analysis of the data, preparing for automated analysis, we are performing a manual analysis i-- a time intensive activity. As such, we were only able at this time to analyze a few dozen logs (a small number, yet these total about 30,000 pages of text!).

The sample size limits the generalizability of our findings. Are there any more patterns by which students explore computer models? What is the actual distribution of such patterns among the population?

Other stages are necessary to test the reliability of our results. In the near future we plan to test the inter-rater reliability for the exploration patterns as well as conduct a comparison between the log data, the video data and the field notes to see whether the inferences we draw from the log data are supported by observation.

REFERENCES

Bruner, J.S. (1973). Organization of early skilled action, *Child Development* 44, 1-11.

de Berg, K.C., Treagust, D.F. (1993). The presentation of gas properties in chemistry textbooks and as reported by science teachers. *Journal of Research in Science Teaching*, 30(8), 871-882.

Eysenck, M.W., Keane, M.T. (1990). *Cognitive Psychology, a student's handbook*, Lawrence Erlbaum Assoc. Publishers: Hillsdale, NJ.

Fischer, K.W. (1980). A theory of cognitive development: The control and construction of hierarchies of skills, *Psychological Review*, 87(6), 477-531.

Frederiksen, J.R., White, B.Y. & Gutwill, J. (1999). Dynamic mental models in learning sciences: The importance of constructing derivatiaonal linkages among models. *Journal of Research in Science Teaching*, 36(7), 806-836.

Frese, M. & Sabini, J. (1985). Action theory: and introduction in Frese, M. & Sabini, J. (Eds.) *Goal Directed Behavior: The Concept of Action in Psychology*, Hillsdale, New-Jersey: Lawrence Erlbaum Ass., Pub.

Gibson, E.J. (1969). Trends in perceptual development. *Principles of Perceptual Development*. Chapter 20, 450-472. Englewood Cliffs, NJ: Prentice-Hall Inc.

Gibson, E.J. (1988). Exploratory behavior in the development of perceiving, acting and the acquiring of knowledge, *Annual Review of Psychology*, 39, 1-41.

Goldstone, R. (1998). Perceptual learning. *Annual Review of Psychology*, 49, 585-612.

Greeno, J.G. (1978). Natures of problem-solving abilities. in Estes, W.K. (Ed.), *Handbook of Learning and Cognitive Processes, Vol. 5: Human Information Processing*. New-Jersey: Lawrence Erlbaum Associated.

Holland, J. (1995). *Hidden Order: How Adaptation Builds Complexity*. Helix Books/Addison-Wesley, Reading, MA.

Kauffman, S. (1995). *At home in the Universe: The Search for the Laws of Self-Organization and Complexity*. Oxford University Press, Oxford.

Kozma, R., Russell, J., Jones, T., Marx, N., & Davis, J. (1996). The use of multiple, linked representations to facilitate science understanding. In Vosniadou, S., Glaser, R., DeCorte, E., and Mandl, H. (Eds), *International Perspectives on the Psychological Foundations of Technology-Based Learning Environments*, Erlbaum, Hillsdale, NJ, 41-60.

Kozma, Russell, J., Johnston, J. and Dershimer, C. (1990). College students' understanding of chemical equilibrium. A paper presented at the *Annual Meeting of the American Educational Researcher Association*, Boston, MA.

Levy, S.T., Novak, M., Wilensky, U. (2005). *Connected Chemistry Curriculum 1.3* Evanston, IL. Center for Connected Learning and Computer Based Modeling, Northwestern University. ccl.northwestern.edu /curriculum/chemistry/.

Lin, H-S, Cheng, H-J (2000). The assessment of students and teachers' understanding of gas laws. *Journal of Chemical Education*, **77**(2), 235-238.

Marbach-Ad, G., Stavy, R. (2000). Students' cellular and molecular explanations of genetic phenomena. *Journal of Biological Education*, 34(4), 200-205.

Mas, C.J.F. & Perez, J.H. (1987). Parallels between adolescents' conceptions of gases and the history of chemistry. *Journal of Chemical Education*, **64**(7), 616-618.

McCullough, Malcolm (1996). *Abstracting Craft*. Cambridge, Massachusetts: The MIT Press.

Niaz, M., Robinson, W.R. (1992). From 'algorithmic mode' to 'conceptual gestalt' in understanding the behavior of gases: An epistemological perspective. *Research in Science and Technological Education*, 10(1), 53-65.

Piaget, J. (1972). The role of action in the development of thinking in Overton, W.F. & McCarthy Gallagher, J. (Eds.), *Knowledge and Development, Volume 1: Advances in Research and Theory*, pp 17-42, Plenum Press.

Resnick, M. & Wilensky, U. (1993). Beyond the Deterministic, Centralized Mindsets: New Thinking for New Sciences, *American Educational Research Association*, Atlanta, Ga.

Rowe, P.G. (1987). *Design Thinking*. Cambridge, MA: The MIT Press.

Samuelson, L.K., Smith, L.B. (2000). Grounding development in cognitive processes. *Child Development*, 71(1), 98-106.

Searle, J.R. (1981). The Intentionality of Intention and Action in *Perspectives on Cognitive Science*, Norman, D.A. (Ed.), 207-230, Norwood, NJ: Ablex Publishing, Hillsdale, NJ: Lawrence Erlbaum Assoc.

Simon, H.A. (1978). Information-processing theory of human problem-solving in Estes, W.K. (Ed.) *Handbook of Learning and Cognitive*, pp 271-295. New-Jersey: Lawrence Erlbaum Associated

Stieff, M. & Wilensky, U. (2003). Connected Chemistry - Incorporating interactive simulations into the chemistry classroom. *Journal of Science Education and Teaching*, 12(3), 285-302.

Uzgiris, I.C. (1983). Organization of Sensorimotor Intelligence, Chapter 5 in Lewis, M. (Ed.), *Origins of Intelligence, Infancy and Early Childhood*, pp 135-190, New-York and London: Plenum Press.

von Hofsten, C. (1993). Prospective control: A basic aspect of action development. *Human Development*, 36, 253-270.

Werner, H. (1957). The concept of development from a comparative and organismic point of view, pp 125-140 in Harris, D.B. (Ed.) *The Concept of Development,* Minneapolis: University of Minnesota Press.

Wilensky, U. & Resnick, M. (1999). Thinking in Levels: A Dynamic Systems Perspective to Making Sense of the World. *Journal of Science Education and Technology*, **8**(1).

Wilensky, U. (1999a). NetLogo, Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL. http://ccl.northwestern.edu/netlogo

Wilensky, U. (1999b). GasLab: an Extensible Modeling Toolkit for Exploring Micro- and Macro- Views of Gases. In Roberts, N. ,Feurzeig, W. & Hunter, B. (Eds.) *Computer Modeling and Simulation in Science Education*. Berlin: Springer Verlag.

Wilensky, U. (2000). GasLab curriculum, Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL. http://ccl.northwestern.edu/curriculum/gaslab/

Wilensky, U., Hazzard, E & Froemke, R. (1999). An Extensible Modeling Toolkit for Exploring Statistical Mechanics. Proceedings of the *Seventh European Logo Conference - EUROLOGO* '99, Sofia, Bulgaria.

APPENDIX I

Variable		**Student ID** **Features**	**13022**	**12999**	**13000**	**13018**	**13039**	**13013**
Features of the student's exploration	**Strategy**	**Pattern**	Straight to the point	Straight to the point	Homing in from one side	Oscillating homing in from two sides	Oscillating homing in from two sides	Oscillating homing in from two sides
	Observation	**Time observing model (min)**	1:06	1:07	0:49	1:09	**1:24**	**2:19**
		Time observing model in each setting (min)	**0:33**	**0:34**	0:12	0:10	0:17	**0:35**
	Explorative-ness	**Number of runs**	2	2	**4**	**7**	**5**	4
	Action	**Time per action**[5]	**0:15**	**0:12**	0:07	0:05	0:03	0:09

Table 2: Students' model exploration patterns. Empty cells are missing data. High scores are bolded.

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[5] Action is defined as any change in sliders or button presses