

An analysis of student' patterns of exploration with NetLogo models embedded in the Connected Chemistry environment

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ABSTRACT

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 model's interface tools? By the kinds of mathematical relationships governing the model's target phenomenon?

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 (Wilensky, 1999a) models to empower the students' manipulation and observation of chemical "entities" at the molecular level as well as the resulting aggregate patterns. These models are embedded in Pedagogica (Horwitz, 2002) scripts that 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. In this paper, we provide an analysis of student's explorations within computerized models, as derived from computer logs of their actions and the model's changing properties.

We have conducted four studies if of patterns of students' model exploration. The studies differ in (a) We observe students employing four distinct patterns; (b) Students are consistent in their use of a specific pattern; (c) Some specific features of these patterns change when the goals change; (d) Half of the students' took advantage of the affordances of more powerful exploration tools to

improve their search for information; (e) Most 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. We then discuss the planned future work in tying these findings in with the students' prior knowledge and learning outcomes.

1. INTRODUCTION

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 (Wilensky, 1999a) models to empower the students' manipulation and observation of chemical "entities" at the molecular level as well as the resulting aggregate patterns. These models are embedded in Pedagogica (Horwitz, 2002) scripts that 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.

A unique affordance for the research on learning within this environment is the intensive logging of students' actions. This intensive logging generates a very large corpus of "click-data", and answers to open-ended and closed questions, for each student. In this paper, 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 need automated tools for exploring patterns from the data.

1.1 THE "CONNECTED CHEMISTRY" CURRICULUM

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. The models used in the current project are a modified version of those originally created for the GasLab curriculum

(Wilensky, 1999b; Wilensky, Hazzard & Froemke, 1999). A free-form version of Connected Chemistry was created by Stieff and Wilensky (2003). In the current project, the models are embedded within a script (Pedagogica, Horwitz, 2002) that structures the interaction of the students with the models.

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 (often named "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) *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.
- (6) *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.
- (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 an example of two screens that are part of the second activity "Changing pressure".

Prior to this section, the students have been introduced to the idea of pressure and that, in the model, it is measured when particles hit the wall. They have explored the qualitative relationship between the number of particles in the box and pressure. In these screens, they are asked whether the pressure goes up immediately after particles are added. Noticing the time lag between pumping particles in and the rise of pressure is the target phenomenon. Thus, the focus is on the dynamics of the process of change between states, in which a change to the system is gradually propagated throughout. They are offered tools (the "cross-hairs") to quantify the values on the two graphs describing these variables over time. In the second screen, an explanation of the phenomenon is described in open form.

Changing Pressure: Activity 2 ...Node: change7

Exploration 2: How does pressure change when particles are added?

Does the pressure go up immediately when particles are added?

Do the two [graphs](#) go up at the same time?

Yes
 No

1. Rerun the model (Press **SETUP**), wait and add **ADD PARTICLES** a couple of times, observe how pressure is affected, and then pause the model (press **GO/STOP**).
2. Use the [cross-hairs](#) to determine the time when the **NUMBER** of particles increased.
3. Use the [cross-hairs](#) to determine the time when the **PRESSURE** correspondingly increased.

Changing Pressure: Activity 2 ...Node: change9

Exploration 2: How does pressure change when particles are added?

1. Run the model, add particles once or twice and then stop.
2. Use the [cross-hairs](#) to determine at what time the two graphs shoot up.
3. Carefully observe the [graphics window](#) when you add particles. You should see that the pressure rises after the particles are added.

Explain why it takes time for the pressure to rise after the particles are added.

because it takes time to reach the wall.

1.2 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 alternative notions about gases such as ordered packing and weightlessness. Lin and Cheng (2000) describe high-school students' failures in understanding Kinetic Molecular Theory as it applies to gases: molecules are pushed down by atmospheric pressure, molecules stay away from heat and molecules expand when they are heated. All three can be related to our macroscopic daily experiences: our gravitation towards the earth, boiling water rising out of a pot and macroscopic expansion upon heating. Mas and Perez (1987) have found that high-school students regard gases as weight-less, reasoning from the macroscopic behavior that gases rise, and 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 the 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.

Wilensky

A fruitful way of approaching the problem of bridging the conceptual and symbolic forms of representing chemical phenomena is the use of 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 used a variety of models in computer simulations, to help students connect the different levels that can be used to describe basic electricity: a particle model, an circuit model and an algebraic model.

Wilensky et al (Wilensky, 1999b; 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, 1999x) 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 students are involved only at the exploratory level and that their explorations are not entirely free but are rather both guided and constrained by a script. The script is designed to guide but also to enable freedom and exploratory flexibility. The affordance for students to connect the observed phenomena with the mechanism or rules underlying the model enables students to view the model as truly computational, and not a prepared “movie” selected by the designers and programmers.

1.3 STUDYING STUDENTS’ MODEL EXPLORATION VIA LOGGING

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. Through logging the students’ actions with the models, we can search for patterns in the students’ investigation.

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. Future papers will report on their relation with the text-based answers, reflecting prior knowledge, knowledge-in-construction and learning outcomes.

1.3.1 FRAMEWORK FOR STUDYING MODEL EXPLORATION PATTERNS AND THEIR RELATION TO LEARNING

A framework (see Figure 1) 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:

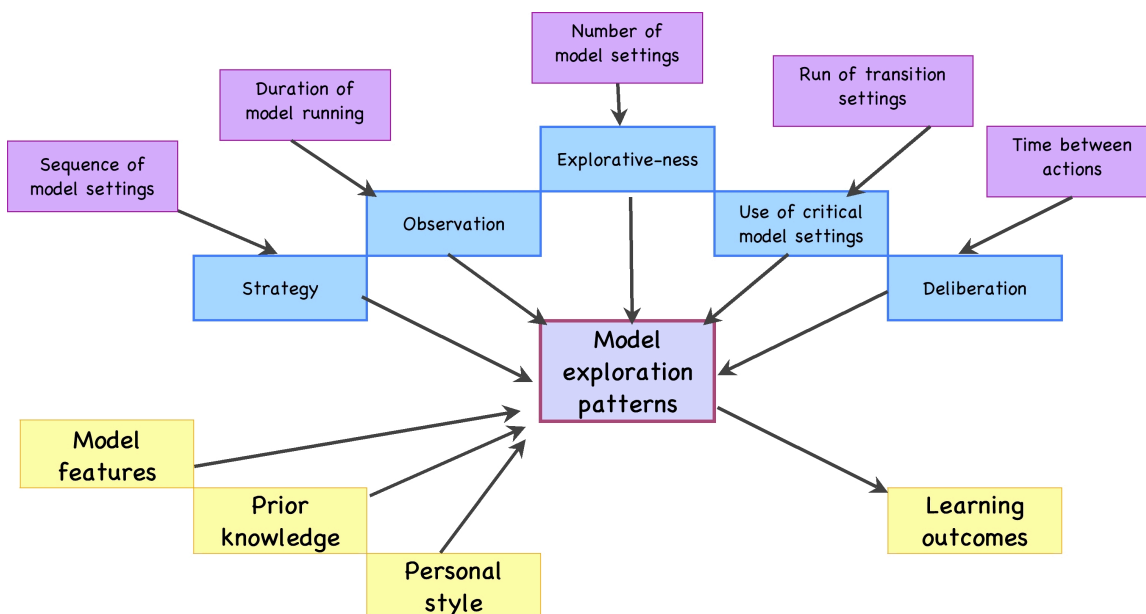


Figure 1: Framework for analyzing students' activities with the Connected Chemistry models, and their relationship to learning outcomes.

1.3.1.1 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. However, 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 few key settings, which 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 students' 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.

1.3.1.2 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 actual reality.

Observation is a necessary pre-requisite 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, there is greater chance such learning would occur.

From the logs of the students' model manipulation, we can obtain the duration that the model was run. It is probable that the duration of the model runs is related to 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.

1.3.1.3 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 exerts 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. 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 planful-ness and deliberation.

1.3.1.4 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: discovering qualitative between variables (e.g., volume and pressure) in terms of "more", "less", "increase" and "decrease"; noticing distinct model behaviors in a particular regime of the parameter space (e.g., exploring "how is pressure determined in the model?" 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), or 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.

1.3.1.5 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, which are 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 richness of the exploration, as reflected in the number of different settings, which a student employs. The other is the use of critical settings.

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.

1.3.2. 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).

2. METHOD

2.1 SAMPLE

The Connected Chemistry environment is in use 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, 7 students were selected. In Study IV, 20 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.

2.2 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.

2.3 ANALYSIS

In logging the students' activities in the Connected Chemistry environment, we collect each action the student takes: multiple-choice and free-text answers, as well as 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 20 students). Once automatization 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.

2.2 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.

3. RESULTS

3.1 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.

We illustrate the patterns by examining two screens (see Figure 2) 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.

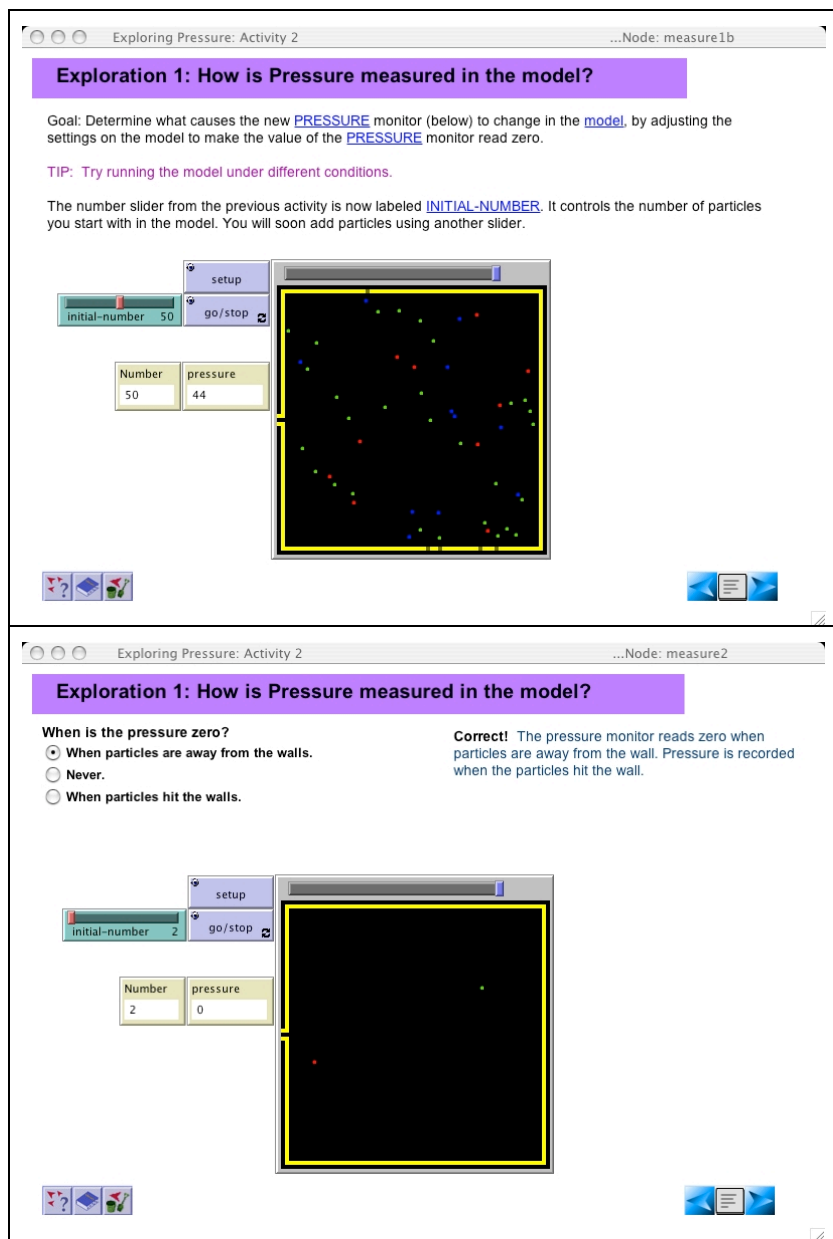


Figure 2: Connected Chemistry “Changing pressure” screen-shots that are analyzed in Studies I and II.

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, as 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 in Appendix I, which notes observation time (overall, per run), time per action and number of runs.

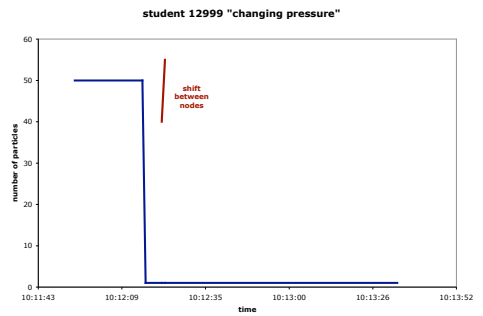
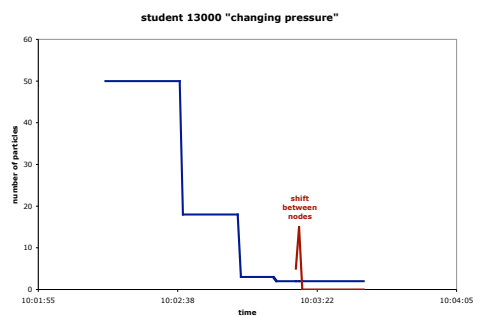
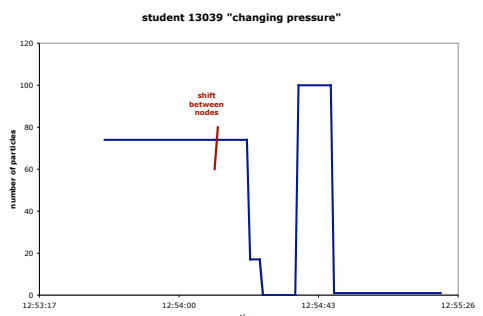
Pattern	Example	Additional characteristics
<p><i>Straight to the point</i></p> <p>(2 students)</p> <p>The most informative state is accessed directly.</p>	 <p>student 12999 "changing pressure"</p> <p>The graph shows the number of particles (y-axis, 0-60) over time (x-axis, 10:11:43-10:13:52). The particle count starts at 50 and drops sharply to 0 at 10:12:09, marked by a red vertical line labeled 'shift between nodes'.</p>	<ul style="list-style-type: none"> (1) Shorter overall observation time, but longer observation time per run (1) Longer time between actions (2) Fewer runs
<p><i>Homing in</i></p> <p>(1 student)</p> <p>The most informative state is gradually approached through decreasing increments.</p>	 <p>student 13000 "changing pressure"</p> <p>The graph shows the number of particles (y-axis, 0-60) over time (x-axis, 10:01:55-10:04:05). The particle count starts at 50 and decreases in steps: 50 to 20 at 10:02:38, 20 to 5 at 10:03:22, and 5 to 0 at 10:03:22. A red vertical line labeled 'shift between nodes' is at 10:03:22.</p>	<ul style="list-style-type: none"> (1) Shorter overall observation time, and shorter observation time per run (2) Shorter time between actions (3) More runs
<p><i>Oscillating</i></p> <p>(3 students)</p> <p>The model oscillates between two regimes, back and forth between high and low values.</p>	 <p>student 13039 "changing pressure"</p> <p>The graph shows the number of particles (y-axis, 0-120) over time (x-axis, 12:53:17-12:55:26). The particle count starts at 75, drops to 0 at 12:54:00, then jumps to 100 at 12:54:43, and finally drops to 0 at 12:55:26. A red vertical line labeled 'shift between nodes' is at 12:54:00.</p>	<ul style="list-style-type: none"> (1) Longer overall observation time, but shorter observation time per run (2) Shorter time between actions (3) Intermediate number of runs

Figure 3: 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.

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 the figure, 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, the 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.

3.2 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 4). The students are asked to figure out 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, 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.

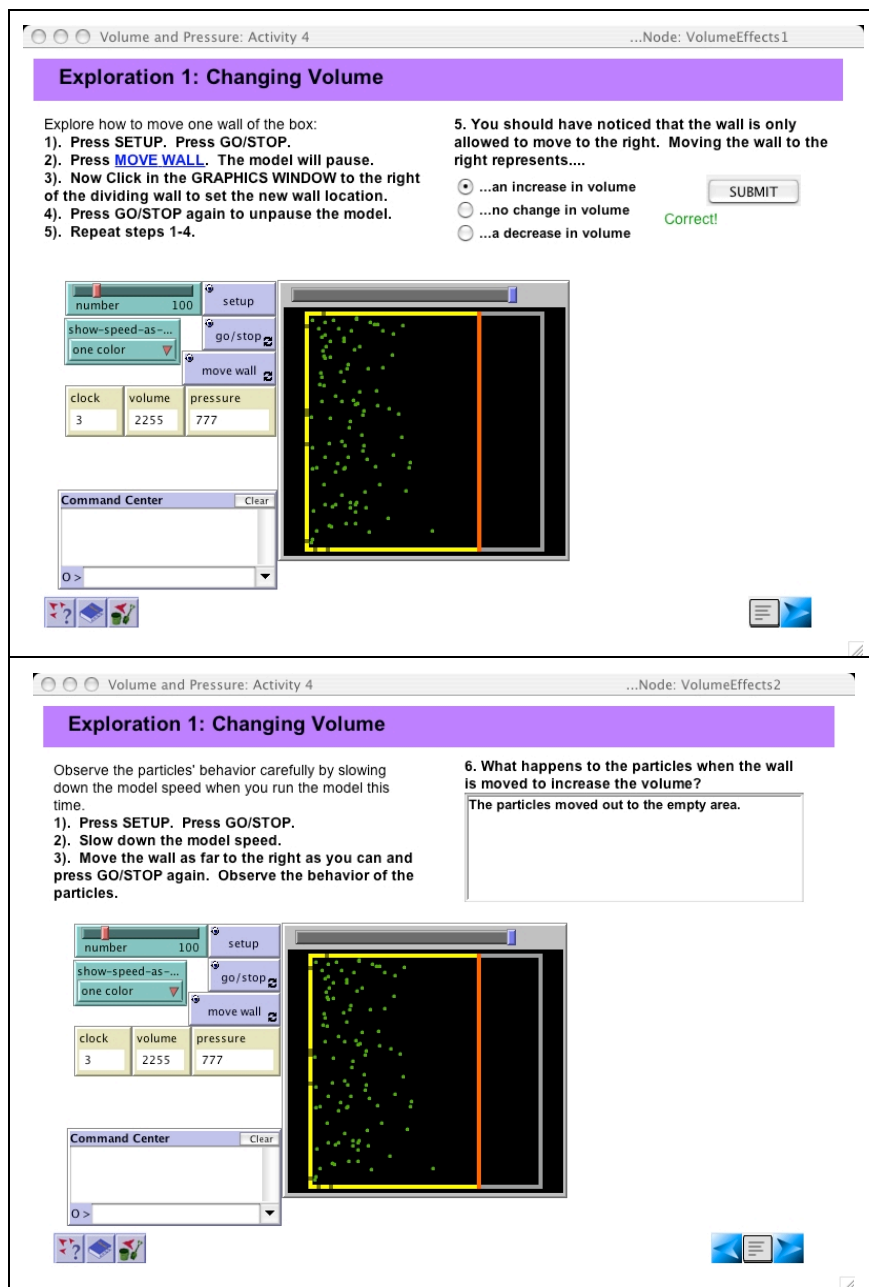


Figure 4: "Volume pressure" activity screenshots.

In the figure below (Figure 5), 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 feature shared by the two: 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.

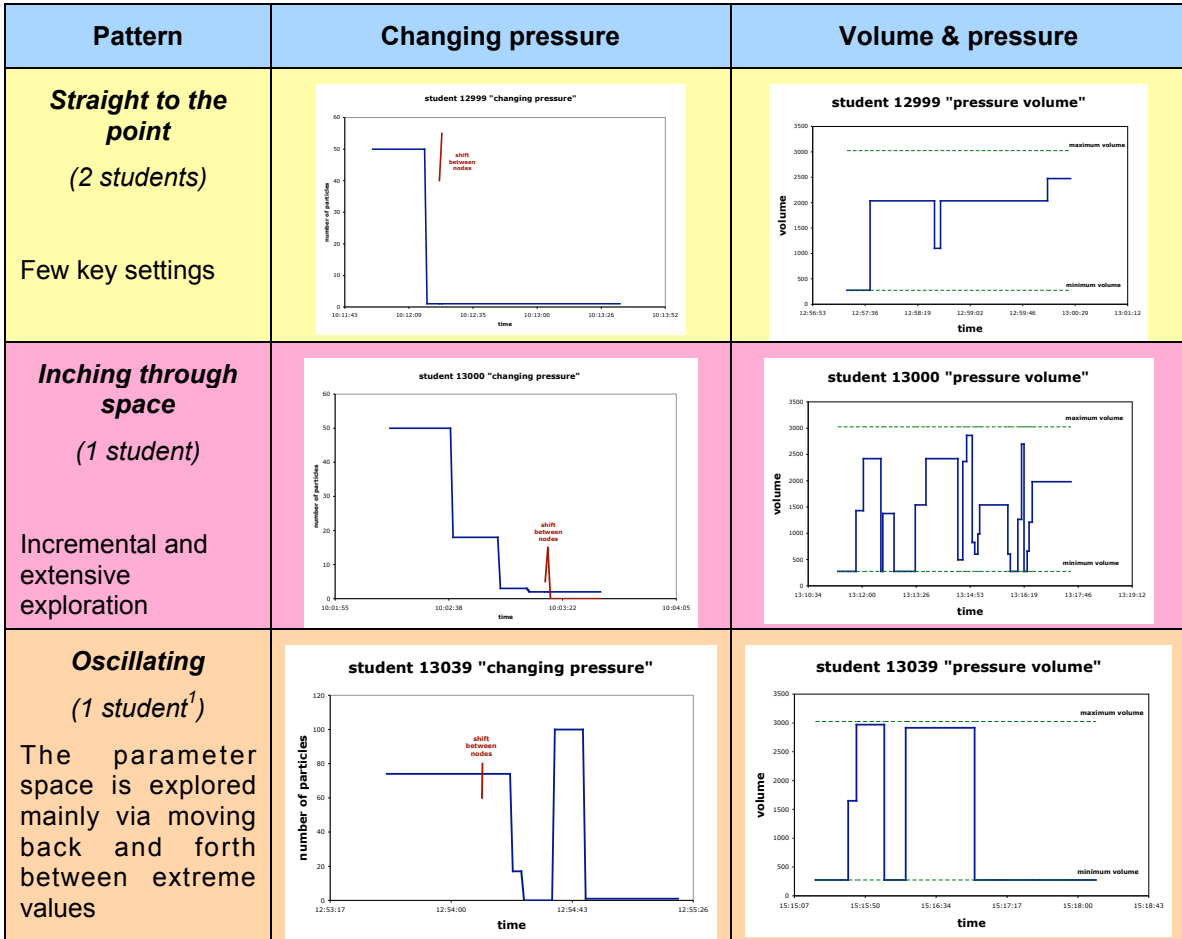


Figure 5: Comparison of two model runs, in activities with different goals. The first run comes from “Changing pressure” with a distinct informative regime. The second run comes from “Volume and pressure” where a wide range of values is more informative. In both activities, X-axis denotes the real time. 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 few key states. The student who “homed in” in decreasing

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

intervals similarly employed many small intervals among successive runs. A student who oscillated between model behavior regimes displayed a similar pattern in both 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.

3.3 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 model². 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 6). 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.

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

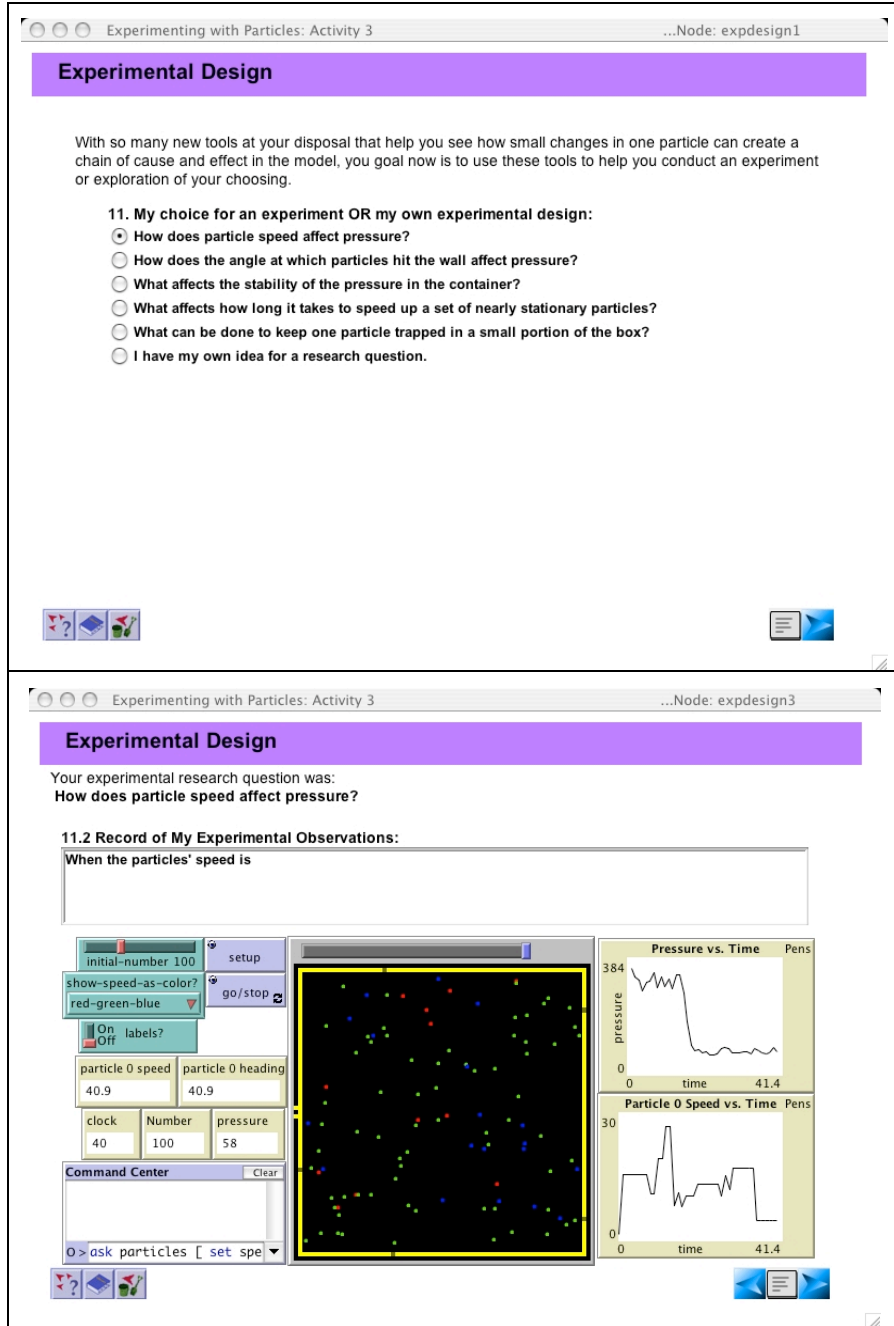


Figure 6: "Experimenting with particles" focal screens.

We have examined the logs of seven students who had all selected the same question: "How does particle speed affect pressure?" The following graphs (Figure 7) 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.

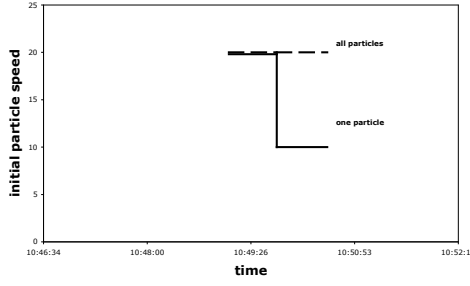
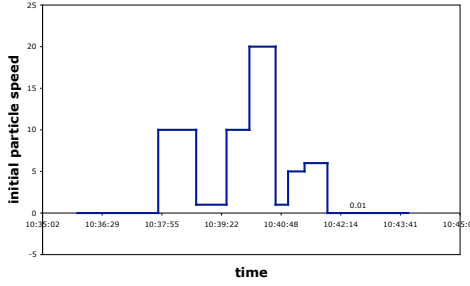
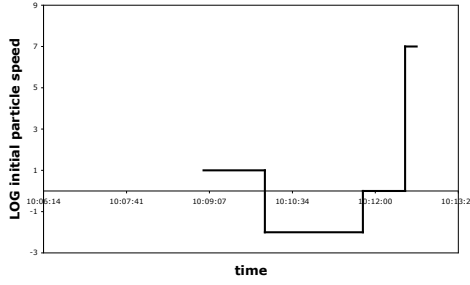
Pattern	Example
<p style="text-align: center;"><i>Straight to the point</i></p> <p style="text-align: center;">(1 student)</p>	<p style="text-align: center;">student 4996 "Experimenting with particles"</p> 
<p style="text-align: center;"><i>Oscillating</i></p> <p style="text-align: center;">(3 students)</p>	<p style="text-align: center;">student 6540 "Experimenting with particles"</p> 
<p style="text-align: center;"><i>Oscillating EXTREME</i></p> <p style="text-align: center;">(3 students)</p>	<p style="text-align: center;">student 5117 "Experimenting with particles"</p> 

Figure 7: “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).

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 3 out of the 7 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 7) 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 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.

3.4 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 kind of goal is presented: deriving a quantitative relationship. In contrast to the previous activities we have described, 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 20 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 ($P = \text{constant} * N$); the second relationship is inverse: as the volume grows, the pressure goes down (Boyle's Law: $P * V = \text{constant}$). 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 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 section 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. 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.

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.

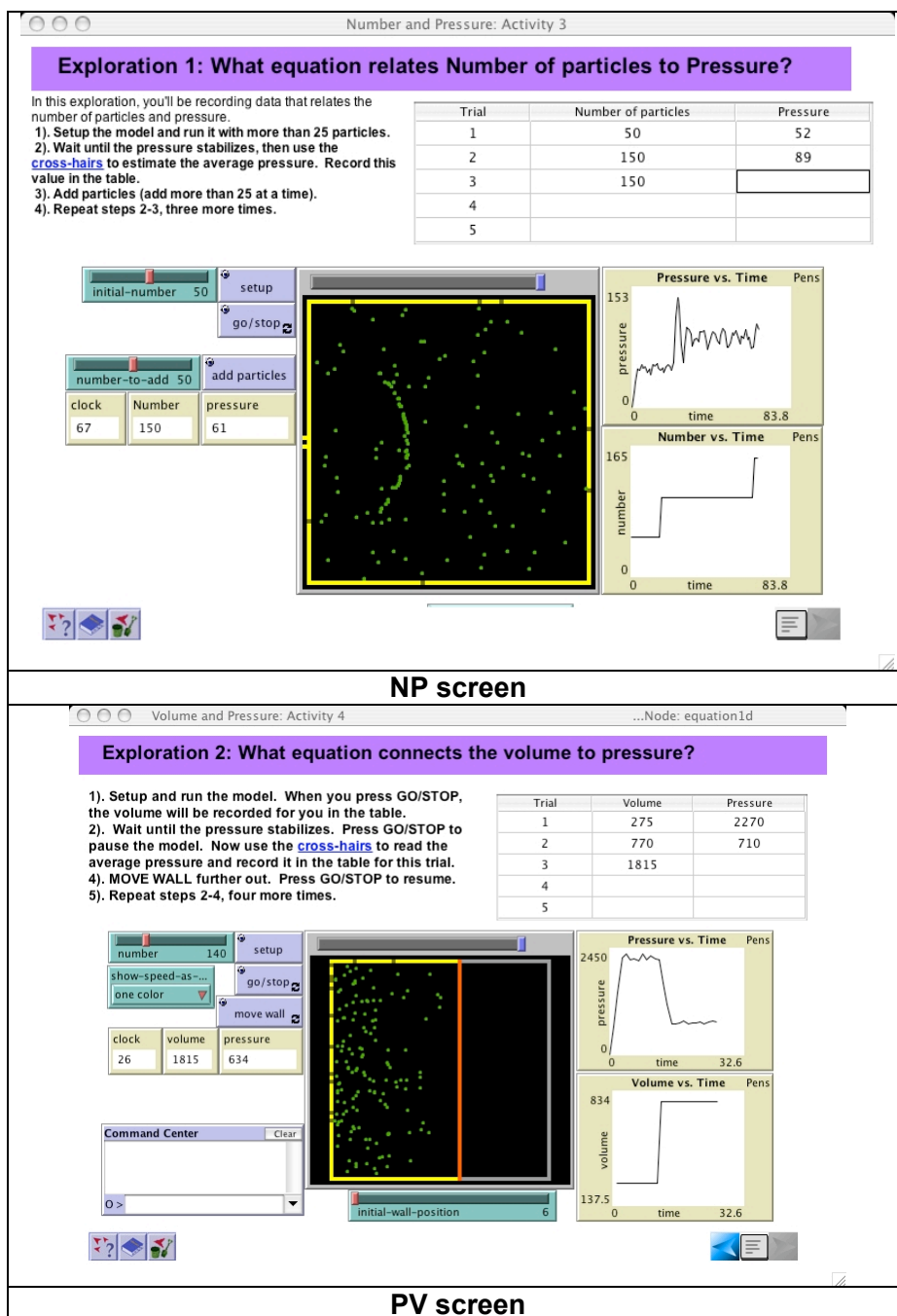
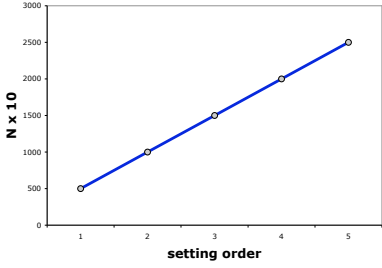
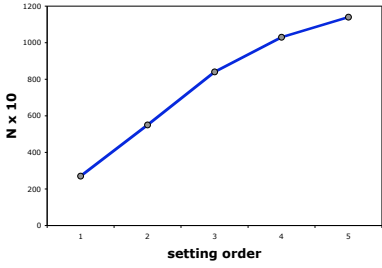
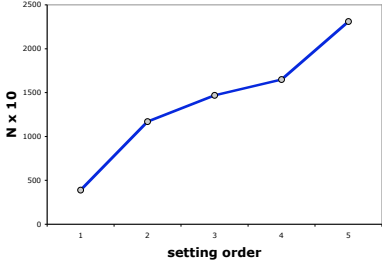



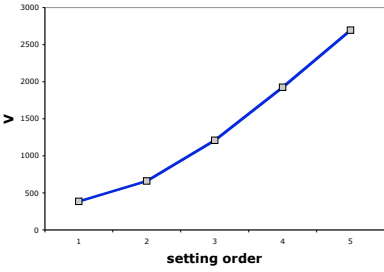
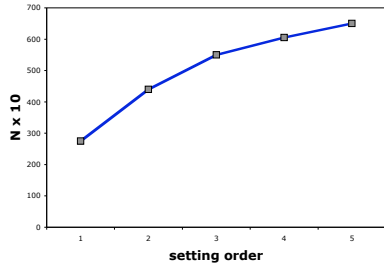
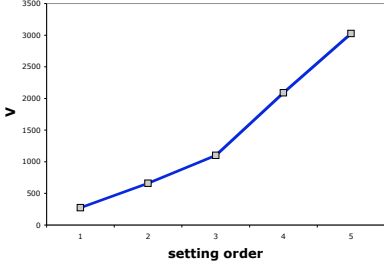
Figure 8: “Number and pressure”, “Volume and pressure” quantitative exploration screens.

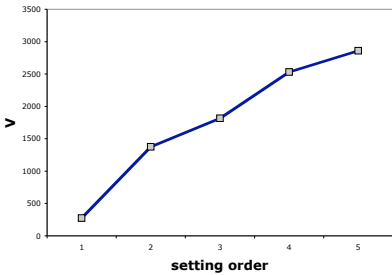
For each student, we have examined the two model rules. We present the exploration patterns separately for each model.

Patterns in NP (Number of particles and pressure) model exploration

NP Pattern	Example												
<p>Constant intervals</p> <p>18 of 20 (80%)</p>	<p>student 4956: settings for NP table</p>  <table border="1"> <caption>Data for student 4956: settings for NP table</caption> <thead> <tr> <th>setting order</th> <th>N x 10</th> </tr> </thead> <tbody> <tr><td>1</td><td>500</td></tr> <tr><td>2</td><td>1000</td></tr> <tr><td>3</td><td>1500</td></tr> <tr><td>4</td><td>2000</td></tr> <tr><td>5</td><td>2500</td></tr> </tbody> </table>	setting order	N x 10	1	500	2	1000	3	1500	4	2000	5	2500
setting order	N x 10												
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4	2000												
5	2500												
<p>Decreasing intervals</p> <p>1 of 20 (5%)</p>	<p>student 4974: settings for NP table</p>  <table border="1"> <caption>Data for student 4974: settings for NP table</caption> <thead> <tr> <th>setting order</th> <th>N x 10</th> </tr> </thead> <tbody> <tr><td>1</td><td>280</td></tr> <tr><td>2</td><td>550</td></tr> <tr><td>3</td><td>850</td></tr> <tr><td>4</td><td>1050</td></tr> <tr><td>5</td><td>1150</td></tr> </tbody> </table>	setting order	N x 10	1	280	2	550	3	850	4	1050	5	1150
setting order	N x 10												
1	280												
2	550												
3	850												
4	1050												
5	1150												
<p>Undetermined</p> <p>1 of 20 (5%)</p>	<p>student 5000: settings for NP table</p>  <table border="1"> <caption>Data for student 5000: settings for NP table</caption> <thead> <tr> <th>setting order</th> <th>N x 10</th> </tr> </thead> <tbody> <tr><td>1</td><td>400</td></tr> <tr><td>2</td><td>1200</td></tr> <tr><td>3</td><td>1500</td></tr> <tr><td>4</td><td>1700</td></tr> <tr><td>5</td><td>2300</td></tr> </tbody> </table>	setting order	N x 10	1	400	2	1200	3	1500	4	1700	5	2300
setting order	N x 10												
1	400												
2	1200												
3	1500												
4	1700												
5	2300												

Patterns in VP (volume and pressure) model exploration

VP Pattern	Example												
<p>Constant intervals</p> <p>4 of 20 (20%)</p>	<p>student 4980: settings for VP table</p>  <table border="1"> <caption>Data for student 4980: settings for VP table</caption> <thead> <tr> <th>setting order</th> <th>V</th> </tr> </thead> <tbody> <tr><td>1</td><td>250</td></tr> <tr><td>2</td><td>750</td></tr> <tr><td>3</td><td>1250</td></tr> <tr><td>4</td><td>1750</td></tr> <tr><td>5</td><td>2250</td></tr> </tbody> </table>	setting order	V	1	250	2	750	3	1250	4	1750	5	2250
setting order	V												
1	250												
2	750												
3	1250												
4	1750												
5	2250												
<p>Increasing intervals</p> <p>4 of 20 (20%)</p>	<p>student 5000: settings for VP table</p>  <table border="1"> <caption>Data for student 5000: settings for VP table</caption> <thead> <tr> <th>setting order</th> <th>V</th> </tr> </thead> <tbody> <tr><td>1</td><td>400</td></tr> <tr><td>2</td><td>650</td></tr> <tr><td>3</td><td>1200</td></tr> <tr><td>4</td><td>1900</td></tr> <tr><td>5</td><td>2700</td></tr> </tbody> </table>	setting order	V	1	400	2	650	3	1200	4	1900	5	2700
setting order	V												
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3	1200												
4	1900												
5	2700												
<p>Decreasing intervals</p> <p>1 of 20 (5%)</p>	<p>student 4974: settings for NP table</p>  <table border="1"> <caption>Data for student 4974: settings for NP table</caption> <thead> <tr> <th>setting order</th> <th>N x 10</th> </tr> </thead> <tbody> <tr><td>1</td><td>280</td></tr> <tr><td>2</td><td>450</td></tr> <tr><td>3</td><td>550</td></tr> <tr><td>4</td><td>600</td></tr> <tr><td>5</td><td>650</td></tr> </tbody> </table>	setting order	N x 10	1	280	2	450	3	550	4	600	5	650
setting order	N x 10												
1	280												
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3	550												
4	600												
5	650												
<p>Combination of constant and increasing intervals</p> <p>Constant intervals, broken by an increase in the middle of the run</p> <p>8 of 20 (40%)</p>	<p>student 4962: settings for VP table</p>  <table border="1"> <caption>Data for student 4962: settings for VP table</caption> <thead> <tr> <th>setting order</th> <th>V</th> </tr> </thead> <tbody> <tr><td>1</td><td>250</td></tr> <tr><td>2</td><td>650</td></tr> <tr><td>3</td><td>1100</td></tr> <tr><td>4</td><td>2100</td></tr> <tr><td>5</td><td>3000</td></tr> </tbody> </table>	setting order	V	1	250	2	650	3	1100	4	2100	5	3000
setting order	V												
1	250												
2	650												
3	1100												
4	2100												
5	3000												

VP Pattern	Example
<p style="text-align: center;"><i>Undetermined</i></p> <p style="text-align: center;">3 of 20 (15%)</p>	<p style="text-align: center;">student 4961: settings for VP table</p> 

The patterns for the group of 20 students are displayed in the following graphs:

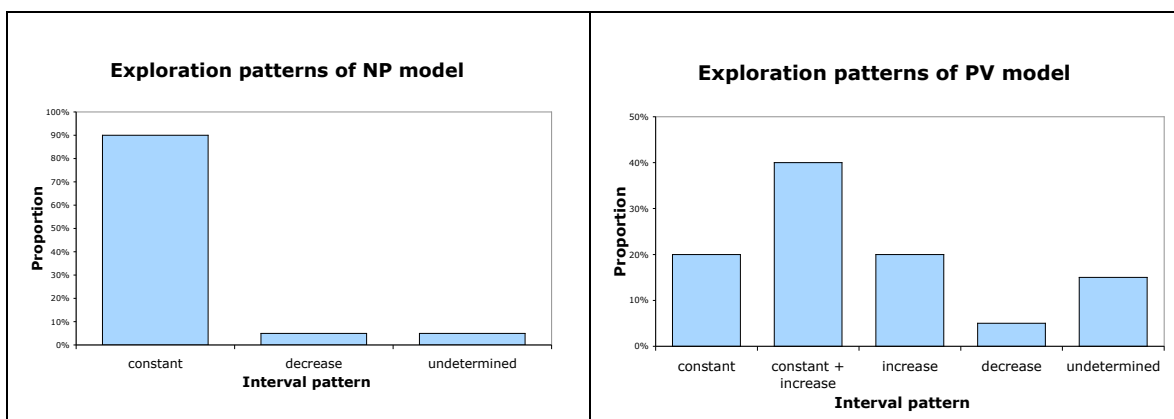


Figure 9: Exploration patterns in a structured activity aimed at deriving a quantitative relationship. Comparison of variation patterns in two activities: Number of particles and pressure (NP) and volume and pressure (VP).

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 18 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 other 14 students 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. The largest group hybridizes two strategies: constant variation and increasing the intervals for the larger volume settings (40%). 20% use a constant intervals on the independent variable, volume, increasing the size of the box in constant increments. 20% adapt to the inverse function completely, by increasing the size of the interval at every successive step.

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.
- (3) In a less scaffolded model with an inverse function underlying the model's behavior, more than half of the students adapted their exploration to the inverse function.

4. 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 1), 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.

4.1 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.

4.1.1 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.

4.1.2 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.

4.1.3 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.

4.1.4 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.

4.2 THESE PATTERNS ARE CONSISTENT, BUT 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.

4.3 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, Hazzard & Froemke, 1999; 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.

4.4 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, 199X). 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.

4.5 RESERVATIONS

While the Modeling Across the Curriculum project currently has thousands of students' activities logs, this is not evident in our analysis. As we are still exploring the data, preparing for automated analysis, the manual analysis is 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. Testing inter-rater reliability for the exploration patterns as well as a comparison between the logs and what the students actually do are planned for in the near future.

4.6 FUTURE PLANS

In this paper, we have described how students interact with the models. This portion of the analysis is embedded in a larger framework, relating prior knowledge, learning paths and interaction with the models, as well as learning outcomes. We plan to test associations between the use of models to prior knowledge and learning, as well as changes which the students experience over time.

We expect that future research will reveal more exploration patterns. However, more importantly, it will help us refine our formulation of these strategies, as we see the students' expertise growing through interacting with the computer-model based curriculum.

Automating the detection of patterns is one of the greater challenges. While most of the variables we have noted (observation time, rate of action) are easily discerned from the logs, and are currently being programmed for analysis, automatically detecting patterns and categorizing them is more of a challenge. Our plan for automating this process utilizes first, second and third order analyses. The first order analysis looks at the actual settings the student has used and determines what regimes of the model parameter spaces have been accessed. The second order analysis looks at the differences between successive settings (first derivative), noting whether the increments are constant, become larger or smaller. The third order analysis looks at differences between the differences (second derivative) to note inflection points, such as the "oscillating" patterns.

Finally, further into the future, after we reach a fuller understanding of the ways by which students engage and interact with our models, this automated pattern detection will allow for feedback to the student and to the teacher, to enable more individual support for learning.

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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 ³	0:15	0:12	0:07	0:05	0:03	0:09

Table 1: Students' model exploration patterns. Empty cells are missing data. High scores are bolded.

³ action is defined as any change in sliders or button presses