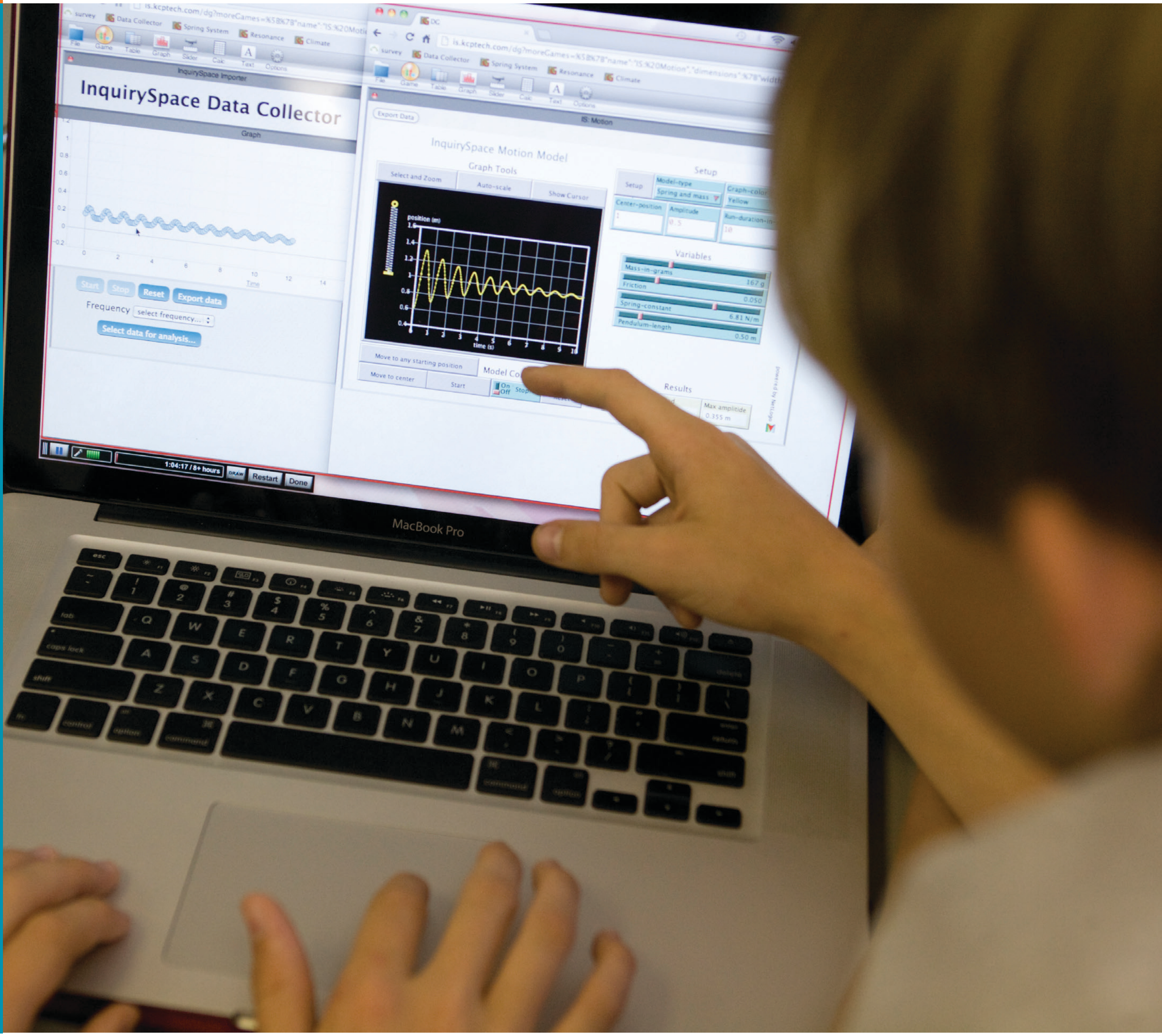
InquirySpace:

A Place for Doing Science



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The Concord Consortium

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A Place for Doing Science

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Project Overview

The overall accomplishment of the InquirySpace (IS) project was to develop and evaluate a powerful, new data analysis package that supports students' reasoning about experiments (Hazzard, 2014; Tinker & Hazzard, 2012). This package provides a sophisticated but intuitive strategy and software tools for student investigations. The IS approach can be used with data from laboratory experiments or data generated by computational models. We provided students with a set of hands-on and simulated experiments and found that students were able to use our approach and tools to effectively explore multi-variable systems and learn from these explorations powerful investigative strategies that can be applied broadly.

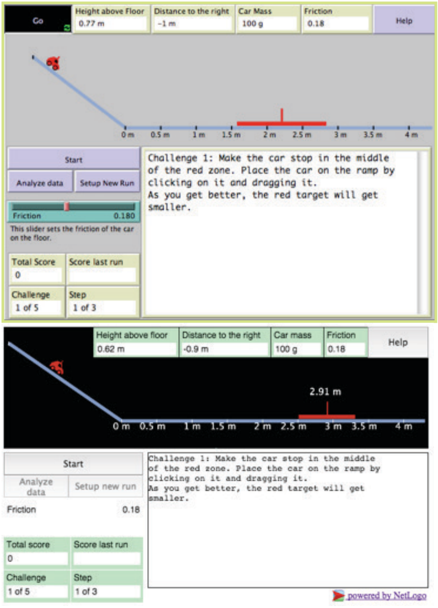
The InquirySpace technologies and the investigative strategies that they enable are important for several reasons:

- **The approach is general.** InquirySpace technologies support almost any experiment with labs, models, or computer games that depend on dynamic data—data that change over time, such as the height of a falling parachute, the Earth's temperature trends, or the oscillations of a spring-mass system. A scientific understanding of many systems involves describing how variables influence the system and predicting the dynamic performance of the system for a range of variable settings. For example, in the parachute system, students study how the size of the parachute and the mass of the parachutist influence the time for the parachute to reach terminal velocity. Our approach is general, allowing students to extract one or more dependent variables from time-series data (e.g., time to reach terminal velocity) and to explore how independent variables (e.g., parachute size and parachutist's mass) influence the dependent variables.

This is an informal summary of the four-year National-Science Foundation-funded InquirySpace project at the Concord Consortium, award #IIS-114762. This report is intended for a broad audience and does not provide detailed citations to the supporting academic literature. It does, however, cite papers generated by this project. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

> “The InquirySpace approach focuses on discovering patterns in real or simulated systems. This is the way most science is organized.”

- **The technology can handle large datasets.** A typical IS experiment involves several time-series datasets, each obtained for unique values of the independent variables. This can result in thousands of individual data values. The goal is to analyze these data in order to describe relationships between the independent and dependent variables. For beginners, this amount of data can be challenging and the act of extracting patterns from these data overwhelming. IS technology reduces this challenge to a series of relatively simple steps and produces visualizations that facilitate understanding.
- **IS uses graphical reasoning**. The key to analyzing IS data is the use of graphs. Graphing provides a way of visualizing large quantities of data that allows the user to easily perceive trends and patterns and to make predictions. The shapes of graphs (i.e., linear, exponential, and periodic) or breakpoints where the shape changes often reveal underlying mechanisms. The noise in graphs can provide clues about experimental error. It is commonplace that the goal in lab work is to summarize results in the form of equations, and while our approach does not forestall this, beginning students often find that graphs are far easier to understand and use for predictions than the equivalent equations. In IS activities, all results can be explained with reference to graphs.
- **IS emphasizes authentic scientific exploration.** The IS approach focuses on discovering patterns in real or simulated systems. This is the way most science is organized, as opposed to the hypothesis-testing paradigm that it too often taught as “the scientific method.”
- **IS demonstrates the role of computers in science.** It is widely acknowledged that computation is the “third pillar” of scientific inquiry. It enables researchers to build and test models of complex phenomena and to manage huge volumes of data rapidly and economically[1]. IS provides accessible tools that do just that, collecting data from models and sensors and giving students control of tools to analyze and visualize these data.



Height above Floor 0.77 m
Distance to the right -1 m
Car Mass 100 g
Friction 0.18

Friction 0.180
This slider sets the friction of the car on the floor.

Total Score 0
Score last run
Challenge 1 of 5
Step 1 of 3

Challenge 1: Make the car stop in the middle of the red zone. Place the car on the ramp by clicking on it and dragging it.
As you get better, the red target will get smaller.

Height above floor 0.62 m
Distance to the right -0.9 m
Car mass 100 g
Friction 0.18

Friction 0.18

Total score 0
Score last run
Challenge 1 of 5
Step 1 of 3

Challenge 1: Make the car stop in the middle of the red zone. Place the car on the ramp by clicking on it and dragging it.
As you get better, the red target will get smaller.

Figure 1. The Ramp Game written in NetLogo and rendered in Java (top) and in JavaScript (bottom). Note: this example used an early version of NetLogo Web—final versions are even more similar.

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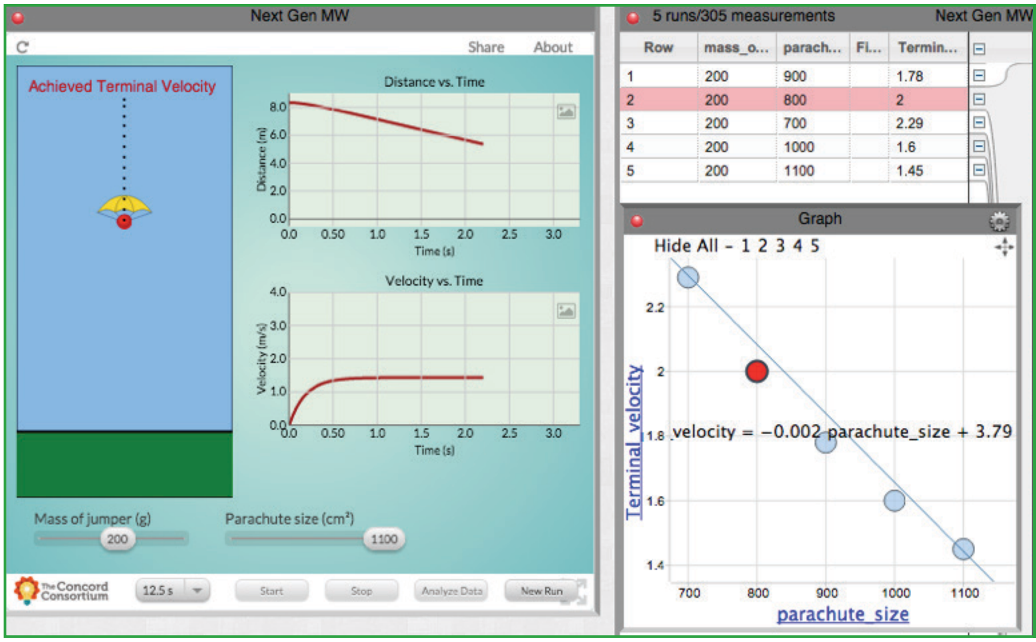
[1] President’s Information Technology Advisory Committee (2005). Computational Science: Ensuring America’s Competitiveness https://www.nitrd.gov/Pitac/reports/20050609_computational/computational.pdf



Mass of jumper (g) 200

Parachute size (cm²) 1100

5 runs/305 measurements

Row	mass_o...	parach...	Fl...	Termin...
1	200	900		1.78
2	200	800		2
3	200	700		2.29
4	200	1000		1.6
5	200	1100		1.45

Figure 2. The Parachute Simulation. Data are generated by dropping the simulated parachute with different masses and sizes. Time-series of distance traveled and velocity are generated as the parachute drops. Runs are displayed by CODAP as a table (upper right) and parameter-space graph (lower right). In this example, the user has attempted to match the final data to a straight line, but this is a poor match, indicating that another relationship is needed.

- **IS should be accessible to under-performing students.** Students can have difficulties with science for reasons that have nothing to do with their science abilities, but because they have had inadequate exposure to critical mathematics, language skills, and lab experiences. IS circumvents these problems by avoiding equations and substituting graphical reasoning, an approach that does not depend on algebra. In the IS project, student reports were made in the form of screencasts, which require no writing and foster reviewing, critical thinking, and collaboration using interactive software. Finally, IS explorations are based on real-time data gathered from sensors and interactive computational models. The use of both sensors and models has been shown to enhance learning for all students, due, no doubt, to the interactive and transparent collection of data provided by these tools, an approach that avoids drudgery and provides immediate feedback in the form of graphical representations.

- **The IS technology can support independent projects.** Student-designed investigations can be challenging for teachers. Students often lack the background, skills, and incentives to undertake their own investigations. Teachers are concerned about the time and intellectual challenges required to support student investigations, as well as the space and equipment needed to support significant projects that students might find interesting. The IS tools and strategies simplify the mechanics of analyzing data and make it possible for secondary students to experience a wide range of science investigations of their own invention, provided that they are based on time-series data. Students can use IS tools with any one or two of the 50-plus sensors that are commercially available or program models in NetLogo Web and link into the tools.

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2. For examples, see http://concord.org/inquiryspace/screencast-examples.

The Technology

Project software combines data acquired from both sensors and computational simulations with a powerful data exploration tool called the Common Online Data Analysis Platform (CODAP) (Finzer, 2014). The InquirySpace project developed technology to embed simulations and sensor data collectors within CODAP and to provide support for students in the process of experimentation. The project also developed a web-based version of NetLogo (NetLogo Web) that simplifies authoring simulations and integrating them with CODAP. This combination of technologies created a flexible environment that students can use for a wide range of investigations of systems.

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Almost all project software runs inside most modern browsers. This has two advantages. First, school IT policy usually forbids the installation of applications, which is risky and difficult to police. Modern browsers have all the software needed to execute IS code. Second, browsers are supported by a wide range of hardware platforms, including desktop and laptop computers, as well as tablets.

Uri Wilensky's group at Northwestern University partnered in the IS project by developing a browser-based version of NetLogo called NetLogo Web. As a result of this development, NetLogo can produce both Java and JavaScript versions of the code. Figure 1 illustrates the two versions of the Ramp Game. This facility was important to support rapid development and testing. NetLogo Web models, when converted to JavaScript, can be embedded in the CODAP environment. Using this capacity, NetLogo was used to prototype several activities. The Ramp Game and Climate Change were prototypes that were converted to JavaScript using NetLogo Web and then used in research.

The one program that is needed for IS that cannot run in the browser is the Sensor Connector, an application developed at the Concord Consortium that runs in the background and passes data from commercial sensor interfaces to the web-based CODAP. For safety reasons, browsers were not intended to interact with the user's hardware, so to support probeware, we needed to make an application to circumvent this problem. The Sensor Connector allows and one or two of the 50-plus sensors sold by PASCO or Vernier to be used to collect data and send it on to CODAP, providing an endless range of possible experiments. The Sensor Connector runs only in Mac OS X and Windows.

Students summarized their IS results by creating short screencasts instead of the usual written reports. Screencasts are video recordings of a student group's computer screen along with the students' voices[2]. Many students have difficulty conveying ideas through writing and are much more comfortable speaking. This is particularly true when the evidence they are using to support their claims is in the form of

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3. See http://concord.org/sites/default/files/projects/inquiryspace/screencasts/fhsgreen12_spring_model.mp4

4. See (Hazzard, 2014) and http://concord.org/sites/default/files/projects/inquiryspace/screencasts/bosgreen6_lab3.mp4 computer graphs and tables, which are difficult to describe in words and far easier to show. Screencast technology allows students to manipulate the screen as they are talking, typically highlighting some aspect of their findings[3]. By limiting the duration of their report, students need to decide which ideas are most important to report. This leads to spirited discussions about their experiment and, often, writing an outline and dividing responsibilities for reporting among members of the group. By requiring short videos, students do not need to learn video editing—instead, they can simply erase the entire video and repeat. The discussions, outlines, and repetitions contribute to the learning experience.

The Learning Progression

The project has developed a sequence of increasingly open-ended computer-based activities using games, sensors, and computational models to develop student investigative skills. To simplify their integration into traditional course instruction, the activities are suitable alternatives to standard treatments of common physical science content such as motion, oscillation, and friction.

The project has developed a way of analyzing data that provides a template that students can use with many kinds of investigations. The basic idea is that a scientific explanation of a system is often stated in terms of how one or more variables affect some outcome. For instance, in one experiment, students explore a spring-mass system using force and motion detectors[4]. A cup is supported by a light springs, various masses are added to the cup, the cup is released, and its vertical oscillations are recorded. The challenge is to investigate the connection between the mass and spring constant (the independent variables) on the period of oscillation of the system (the dependent variable). A distance sensor on the floor generates a time-series (students learn to call this a "run"), which can be graphed as the height of the mass above the floor as a function of time. Then one parameter—say, mass—can be changed systematically and new runs are made that each generate a different time-series from which period (the dependent variable in this case) can be calculated.

After exploring several different values of the mass and observing different periods, students can use CODAP to graph the period as a function of the mass. This graph appears as a series of points, each representing the results of one run. Students can use additional graphs to explore the influence of the other independent variables. A description of these graphs can provide a complete explanation of the effect of each independent variable.

We have named the type of cognition necessary for students to successfully engage in this form of inquiry-based experimentation, Parameter Space Reasoning (PSR). PSR is associated with planning experiments, operationalizing a set of parameters, navigating the parameter space through multiple experimental runs, identifying patterns in parameter space plots, and reflecting on sources of error (Lee et al., 2014).

The project relies heavily on having students read and interpret graphs accurately. Based on our observations of student weaknesses in this area, we developed a Ramp Game in NetLogo Web to introduce the IS approach (Figure 1). To succeed in the game, it is essential for the player to read graphs and engage in PSR in order to move through five progressively more difficult challenges. Following this game, students use the same data graphing tools to investigate real and virtual spring-mass systems, and a parachute simulation (Figure 2). After these explorations, students are encouraged to undertake investigations to answer their own questions.

PSR is useful in many experiments—both lab based and simulated—wherever the experiments generate time-series datasets that depend on one or more independent variables. To enable students to undertake their own hands-on investigations, the project developed two activities that can accept data from one or two probes using the Sensor Connector, and pass those data to CODAP. To support projects based on student-generated models, we also have made it possible to connect any NetLogo Web model to CODAP. Any programmer who can use NetLogo and HTML can link a NetLogo Web model into CODAP (Finzer & Tinker, 2015). We plan to simplify this process in the future.

Research Results

The Parameter Space Reasoning approach raises a number of questions. Can students understand all the parts of PSR: the two kinds of graphs, the difference between parameters and outcomes, the relationship between points in parameter space and a time-series? Can they master all the reasoning steps in PSR? Can students coordinate this approach to produce a coherent explanation of the system being investigated? Can they use PSR to undertake their own investigations? To answer these questions, the project undertook three research studies.

The PSR Pre-Post Assessment

To determine whether students were able to understand and apply PSR, we included five aspects of PSR in pre- and post-tests (Lee, 2014). We looked for gains in the following tasks: understanding time-series graphs, obtaining an outcome, making a parameter-space graph, explaining the patterns in a particular graph, and explaining unusual features. Gains in these five elements were measured by an assessment consisting of 28 test items that were embedded in four investigation contexts of varying degrees of transfer. Two investigation contexts addressed experiments that were part of the IS materials (near transfer); the third addressed a medium transfer context involving distance and time graphs of a long distance running situation; the last context addressed a far transfer situation related to multivariate relationships in everyday gardening. The assessment passed Rasch analysis tests that determined the reliability of the assessment and other psychometric properties.

The PSR assessment was administered to a total of 231 students enrolled in three different high school physics courses. The assessment was used as a pre-test (before using any IS materials) and a post-test (as the last IS activity). Overall, students scored significantly better on the post-test, indicating that they did increase their understanding of PSR and its application to near and medium transfer contexts, but not to far transfer. There were significant differences in the gains by students in different courses. The net gains observed in this initial research were not as large as expected, suggesting that improvements in the assessment, technology, teacher preparation, class time, and materials might result in larger gains in PSR.

Bayesian Knowledge Tracing Analysis of Game Performance

The Pre-Post PSR Assessment only indicates that students PSR scores increased, but not why. To gain additional detail about student progress in understanding the relationships in a mechanical system, the project undertook a detailed analysis of student learning patterns as students played the Ramp Game that was administered just after the pre-test.

The Ramp Game is played by groups of two to four students and consists of five levels (with several steps at each level) in order of increasing difficulty. In order to study patterns of learning, the software recorded all parameter changes students made as well as students' scores in each level. We analyzed student progress at 447 game levels produced by 64 student groups in two physics classrooms using a computational algorithm called Bayesian Knowledge Tracing (BKT). We improved conventional BKT algorithms substantially to increase the speed of BKT calculations by at least 10,000 and, more importantly, to increase its precision. We named this advanced version Monte Carlo BKT or MC-BKT (Gweon et. al., 2015a; 2015b).

Using MC-BKT, we were able to identify seven distinct learning patterns. As expected, one pattern showed students not improving in scores and another pattern displayed students' quick mastery of the knowledge associated with a level in the game. More interesting were the five patterns showing students' struggles followed by successful learning, but with different rates and success (Lee et al., 2015; Pallant, Lee, & Kimball, 2015).

Observational Analysis of Screencasts

To gain additional insights on student thinking, the project created screencasts of some student groups as they worked with the IS tools for full class periods. This research used the same technology as the screencasts used for student reports, but the "research" screencast recordings were left on for the entire class period.

For the Ramp Game, screencasts provided an independent way to identify student learning patterns in order to determine whether there was a match between the patterns identified by MC-BKT analysis and those identified by experienced educational researchers (Lee, et al, 2015). We collected screencasts from 21 of 64 student groups who played the Ramp Game, representing 32% of the data analyzed with MC-BKT. Using a structured analysis of these screencasts, we were able to identify all but one BKT cluster and even observed three sub-clusters within the remaining MC-BKT cluster. There was 84% agreement between the clusters identified through video analysis and through MC-BKT. The analysis also told us that students learned more about the physics used in the game than about PSR.

- Students responded strongly to graphical anomalies.
- Students coordinated data representations and features to make sense of puzzling data.
- Even disengaged students frequently reasoned about patterns in their data, about what constituted acceptable variation, and what data should be rejected or ignored.
- Students moved from viewing graphs as tasks they had to perform to viewing them as tools to help them understand an experiment or a concept (Stephens & Pallant, 2015).

We are also interested to learn if students can apply the PSR approach to questions of their own.

Broader Implications

This project has demonstrated that typical students can learn to use an integrated set of computer-based tools to undertake sophisticated, open-ended investigations that are similar to the approach used by scientists. This allows students to experience the practices of science as envisioned in the NGSS standards. Although the project focused on secondary physics and physical science content, it should be widely applicable. All science disciplines depend on investigating cause and effect, which is essentially the impact of parameters on outcomes, or PSR.

The goal of InquirySpace was to test a unique approach to scientific exploration before undertaking an investigation into the applicability of this approach to diverse students. For this reason, we have no data on student diversity. However, one research site was a middle school public charter school that randomly selected inner-city students. It was clear from observing these students that many had had very limited prior science lab experience and were under-performing in language skills and algebra. However, most of these students were able to perform the experiments and generate screencast reports. Although further research is needed, it seems likely that the combination of real-time data acquisition and display, graphical reasoning, and screencast reports coupled with the avoidance of algebra and writing will broaden access to authentic scientific explorations.

Teacher uptake of inquiry activities is hindered by the pressures to give students exposure to the maximum amount of content. We have found a way to combine this emphasis on "doing science" with instruction of disciplinary core ideas by having students investigate systems that illustrate relevant science content. This is essential for wide adoption of open-ended project-based teaching.

Other innovations of the project that will have broad impact include the creation of NetLogo Web and the MC-BKT algorithm. The creation of NetLogo Web is important because there are tens of thousands of NetLogo users who can now, for the first time, create models that run in any browser. The MC-BKT algorithm we developed is likely to have a broad impact on educational research because it is faster and more accurate than other BKT algorithms. This means that it might be feasible for the first time to do this analysis in real time as a student is playing the game. This, in turn, means that automated guidance based on MC-BKT might be able to automatically scaffold student learning. The project's video analysis strongly suggests that BKT was detecting meaningful learning patterns. In the future, MC-BKT could provide real-time assistance based on student learning patterns.

Project publications

Gweon, G.-H, Lee, H.-S., Dorsey, C., Tinker, R., Finzer, W., & Damelin, D. (2015). Tracking student progress in a game-like learning environment with a constrained Bayesian Knowledge Tracing model. In J. Baron, G. Lynch, & N. Maziarz (Eds.), *Proceedings of the Fifth International Conference on Learning Analytics and Knowledge* (LAK '15) (pp.166-170). Poughkeepsie, NY: Society for Learning Analytics Research.

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Tinker, R., & Hazzard, E. (2012). InquirySpace: A space for real science. *@Concord,* 16(2) 8-9.