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The Concord Consortium
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Perspective:

New Horizons: Ushering in a Transformative New Technology Era

By Chad Dorsey

At the Concord Consortium, we're always on the cutting edge of STEM educational technology. Sometimes that cutting edge feels razor sharp. This is one of those times. We are very close to seeing current capabilities and long-term potential converge in ways that will radically open up the technology landscape and accelerate the development of an immense range of activities.

Educational technology design and development is exciting because it never stops. In fact, it is always hurtling forward. To understand where we should focus, we must look far ahead. While many ideas on the horizon may seem futuristic, they are often very near, with significant advances within as little as five to ten years. To unlock the full potential of these opportunities for STEM teaching and learning, however, we must understand them well and anticipate them early.

Natural input

In order for educational technology to be useful, learners must be able to communicate their ideas and intent to it. The modern computer era has offered only a limited set of input methods—until recently, the mouse represented the only real innovation in input in almost 40 years. This drought has finally begun to abate, with touchscreens popping up everywhere. Learning is now possible for a cohort of learners too young to navigate traditional keyboards and mice. Though the wide use of multi-touch technology for STEM learning is still in its infancy, the Concord Consortium's cutting-edge work with large-format multi-touch screens for museum exhibits represents one example of a new design paradigm. As multi-touch tables and walls become readily available, new modes of collaboration and highly interactive environments will blossom.

But touchscreens represent only one of the many ways new input can transform teaching and learning. Learning happens through animated conversation, verbal exchanges, and natural gestures, and is mediated by emotion. All of these will soon be available for input. Speech technology is proceeding at a breathtaking pace, as anyone who has interacted with Skype and Google's translation tools or the marvelous Amazon Echo can attest. Google Docs are now fully voice compatible. Apple is integrating Siri into its newest version of OS X. Natural speech input is here to stay. We at the Concord Consortium are actively exploring the broad potential spoken language technologies offer for educational research and learning.

Gestures are similarly essential to communication, conveying information beyond the spoken word and providing cognitive support. Gesture sensing and response technology are rising quickly, from Leap Motion's consumer device to Google's tiny, impressive, radar-powered Project Soli. We are exploring this future through active research collaborations into gesture-based control of models and simulations.

The list continues. Conversational, chat-based input examples are bursting onto the scene—watch Facebook's M, Google, and a raft of startups. Facial recognition technology is already mainstream. And headband brainwave sensors from companies such as Emotiv sense affective qualities such as focus, engagement, and excitement. These technologies have the potential to make learning personal in radical ways and tune it to optimal conditions, turning the vague "teachable moment" into a research reality.

Artificial intelligence

Many of these possibilities owe a huge debt to a revolution that has been brewing for almost as long as computers themselves. The beginnings of artificial intelligence (AI) in the late 1950s whip-sawed from stunning advances to deep cooldowns that made many write off the field entirely. Google brought "deep learning"—and much of the AI community—back from a deep sleep in 2012, as algorithms dove into the YouTube universe and independently identified an image—a cat, of course! With the starting gun officially fired, advances shot out of the gate. AI applications can now categorize real-world objects in real time, surpass humans at large-scale image recognition, learn to read unknown alphabets, and beat humans at video games. Now they have roundly beaten a world champion at the game of Go, a feat thought only months earlier to lie still a full decade away.

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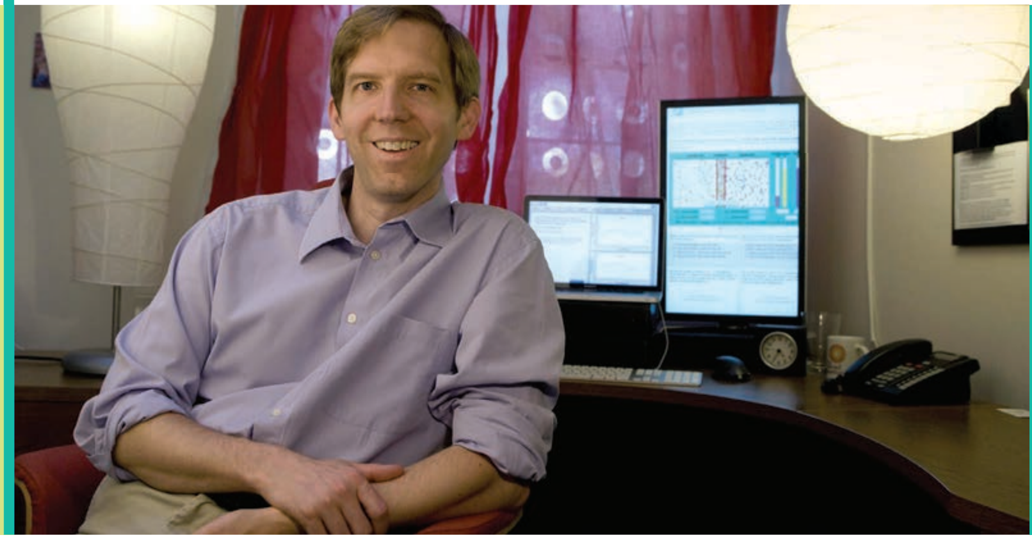

Educational technology has only begun to imagine the possibilities of these advances, but they are certainly manifold. We are currently exploring 1) the application of machine learning to provide real-time analysis and feedback on student argumentation, 2) the use of deep learning and other techniques to provide guidance to teachers and students playing genetics games, and 3) the use of data-mining techniques to analyze learner-generated data and spur actions that improve teaching and learning.

Internet of Things

One result of the decades-long reign of Moore's Law is the broad "Internet of Things" (IoT). The smartphone revolution has quietly ushered in fleets of tiny, low-cost, high-powered computing devices. Now their astonishing ramifications are becoming clear. With entire systems on a single chip, devices can be programmed with ease and placed into almost anything. Devices the size of a postage stamp monitor temperature and airflow in every room of a remote manufacturing facility and track precise locations and engine use across full vehicle fleets.

The second wave of this revolution is already here: drones, intelligent toys, and tiny tracking devices for cars, keys, and even kids. But the educational potential of these devices has yet to be fully explored. Some projects have rightfully made news—the wonderful (now amazingly $5) Raspberry Pi comes to mind—but the time is ripe to recast the IoT for education more broadly. If sensors can monitor assembly-line conditions, they can also turn a science laboratory into a data-streaming environment or bring remote ecosystem monitoring to children's fingertips. The Concord Consortium's vision introduced the probeware revolution decades ago. Today, IoT technology offers an equally revolutionary set of opportunities for teaching and learning.

Virtual reality

Having survived a full cycle of bust-and-boom expectations, virtual reality is now back, and this time it is delivering on all its promises. From the breathtaking HTC Vive and consumer-ready Oculus Rift to the barebones, yet amazing, Google Cardboard, immersion into new worlds is coming to the masses in an entirely new medium of expression and experience. Full implementation of this brave new world is yet to come. Movies and games will arrive first. *The New York Times* is already experimenting with its potential for journalism. But the opportunities for education are still wide open. What will happen when we transport learners inside a chemical reaction or drop them on an alien world to collect samples as scientists? Google Expeditions shows one of the current great examples—allowing a teacher to "drive" a classroom of students to gape at towering Mayan ruins, then teleport them atop the Great Wall of China, or take them on a global geology tour from Ayers Rock to Arches National Park.

Virtual reality is powerful stuff, creating "presence" that tricks our brains into thinking we're truly somewhere else. Full, persistent virtual reality worlds will offer radically new inquiry science opportunities, with experiments playing out not across minutes, but over months. And its sister technology, augmented reality, will layer notes and real-time visualizations onto reality, annotating our real-world views of everything from pond ecosystems to intricate engineering processes.

As always with such revolutions, we don't know exactly where this will all lead. What is clear is that tremendous learning transformations lie on the near horizon. We invite you to join us as we explore the possibilities.

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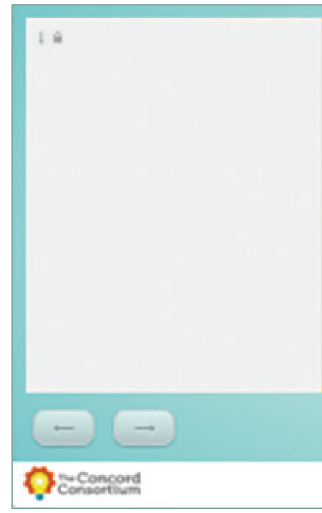

GRASPing Invisible Concepts

"Hand waving" is often used to characterize a nebulous explanation that's short on details. But could the literal waving of hands—or other gestures and movements of the body—be key to the process of reasoning about scientific concepts? The notion that human cognition is rooted in the body is not new, and a growing research effort is emerging to test the idea. So, how *can* we determine the relationship between body motion and learning? If we uncover a relationship, can we use that knowledge to enhance learning? Finally, is it possible to use discoveries from this research to create learning environments using body motion to help students build better mental models of difficult concepts?

The GRASP (Gesture Augmented Simulations for Supporting Explanations) project, funded by the National Science Foundation, is exploring these questions by investigating how middle school students learn important science topics that are difficult because their explanations are hidden from everyday experience. For example, middle school students learn that conductive heat transfer is caused by interactions resulting from the ceaseless motion of molecules of matter. However, few are able to explain the warming of a spoon handle set in a cup of hot tea. Students do not have robust mental models on which to build explanations for such abstract, unseen causes. In this case, they have only a vague view of the underlying particulate nature of matter.

The Concord Consortium developed the Molecular Workbench (MW) software engine and hundreds of simulations built with it to help students visualize the interactions of atoms and molecules. We have found that students from kindergarten through college can learn the patterns of movements of the unobservable world of particles by experimenting with MW simulations, and they can explain the causes of phenomena such as heat transfer or the gas laws using mechanistic arguments. The GRASP project is now examining more closely how students learn with simulations and how to enhance learning through gestures.

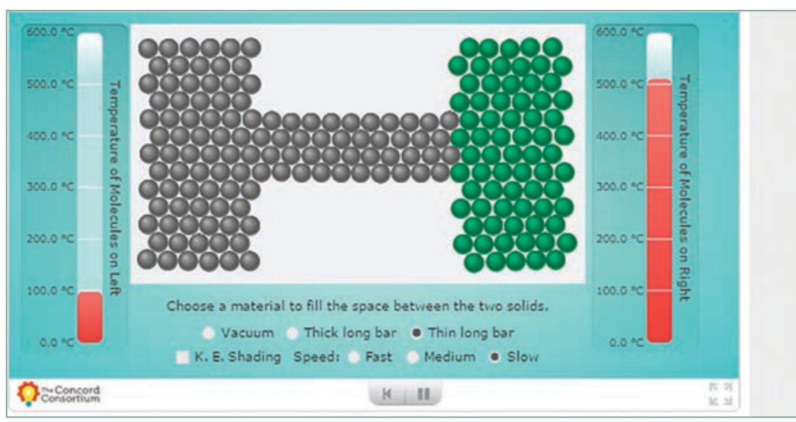

Figure 1. In the heat transfer simulation, molecules transfer energy as they bump together. The Leap Motion controller senses the student's right hand (right) and selects the corresponding block of molecules (the green "balls"). As the student shakes his fist at different rates, the molecules are cooled or heated, and energy is transferred through the connecting bar.

Research

The research of learning with body motion or embodied cognition is led by Robb Lindgren, Principal Investigator, David E. Brown, Co-Principal Investigator, and their graduate students at the University of Illinois at Urbana-Champaign (UIUC). They have

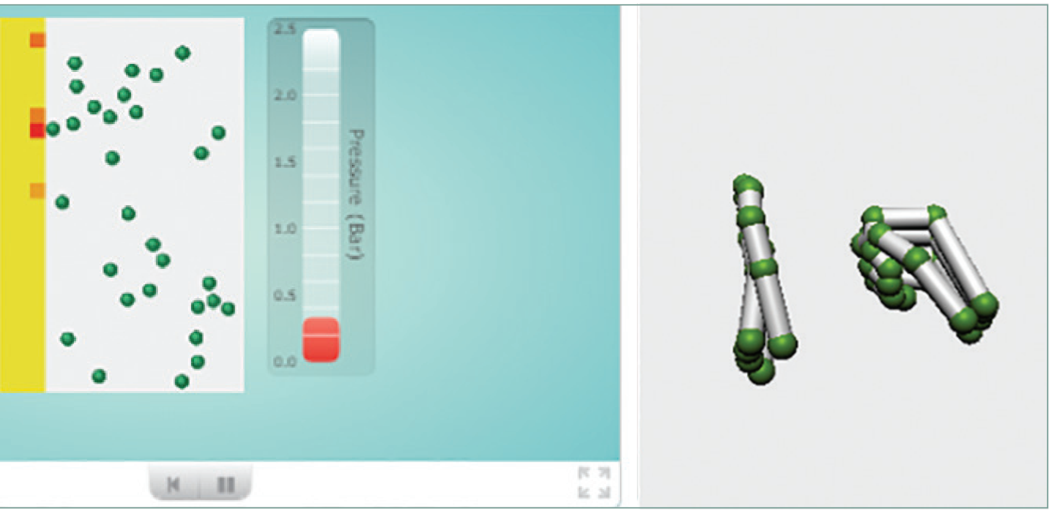

Figure 2. Gesture control for the pressure vs. volume simulation is governed by tapping the finger or fis of the right hand onto the open palm of the left hand to indicate how fast molecules bump into the plunger of a piston. Red squares on the plunger (yellow bar) mark that impact; the red dots fade shortly after impact.

By Nathan Kimball

constructed a framework for the detailed investigation of students' learning and the use of body motion using one-on-one interviews with students. The researcher's role is to ask questions that uncover the student's initial understanding of the topic and to provide both physical and computer models, relevant facts, and scaffolding questions to help orient students and build their understanding while repeatedly asking for refined explanations. Interviews may last up to 40 minutes, although the nature of the questions varies depending on the student's understanding.

Often, students incorporate hand motions to help explain their ideas, and the interviewers encourage them with the goal of discovering what gestures students naturally find helpful. If students are reluctant to gesture, the interviewer prompts them to try different motions that evoke a mechanism or process in the phenomena to see if it helps build their understanding. For example, to demonstrate how molecules create pressure on the plunger of a piston, the student would tap their fingers or fist into an open palm, tapping quickly for high pressure and slower for low pressure.

The interviews provide a rich view into student thinking and have yielded new insights about the way gestures can enhance students' ability to explain difficult phenomena. Our research has found that the role of gesturing in explanation takes on a variety of forms. Students may develop gestures spontaneously in the course of an explanation, sometimes using gesture as a tool for thinking through physical actions, even watching their hands while describing the motion. For other students, gestures develop seemingly subconsciously, their hands constructing tentative representations of the ideas they are formulating. In interviews, researchers have tried to make students aware of their hand use and have them develop it further. Analysis of the interviews shows that acknowledging and having students reflect on and refine gestures improves explanations. Bringing gesture to a conscious level appears to be a useful scaffolding tool, which indicates that it may present a pedagogical opportunity when used with new technologies.

Gesture input technologies

The UIUC GRASP team and the Concord Consortium are currently exploring the synthesis of the learning potential of computer simulations with the scaffolding benefit of gestures by using new computer input technologies to control the simulations using body motion. Gesture input devices have been around for quite a while, with Microsoft Kinect as perhaps the best known example popular with gamers. More recently, simpler and less expensive technologies have emerged. Our initial work utilizes the $80 controller made by Leap Motion for its low cost, small size, ease of installation, cross-platform (PC and Mac) flexibility, and compatibility with our browser-based online simulations. Gesture control is not used to operate the computer's "widgets"—buttons, sliders, or checkboxes—but to manipulate the central actions and elements of the phenomena the simulations represent. Gesture input should allow students to *feel* and *participate* in the phenomena.

The focus of our work at the Concord Consortium is to apply what we have learned from the interviews to design and build gesture-controlled simulations that also take into account the capabilities of the Leap Motion controller. Although the Leap is made to detect hands, it does not reliably detect motions of the fingers in all orientations, and the user's hands may obscure each other relative to the device. Since the technology has not reached the point where any imagined motions can be detected, we have sometimes in our software designs modified the most physically meaningful motions so the device can interpret them. We are also working on designing a user interface that will seamlessly instruct the user how to interact with the simulation while providing for students' inquiry and experimentation.

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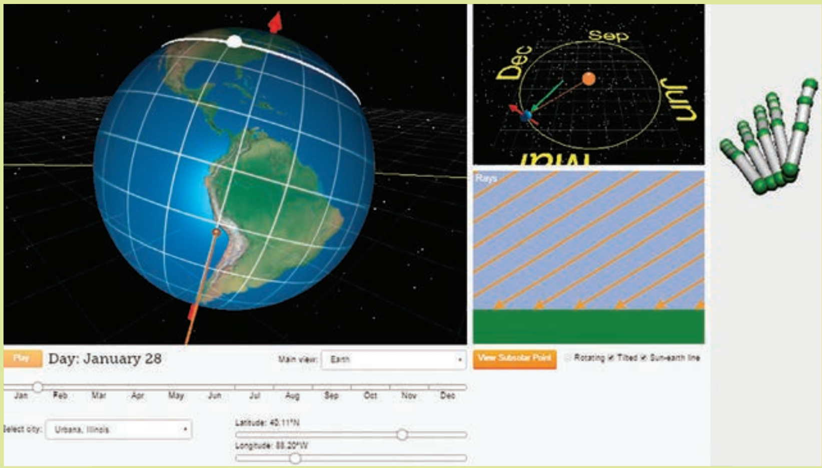

Figure 3a. The seasons simulation focuses on the angle at which sunlight strikes the Earth's surface, represented in the lower right window. When the angle of the student's hand matches the sun's angle for the given position on the Earth's surface, the light rays turn yellow. As the student rotates her hand through the changing sun angles over the course of the year, the Earth orbits.

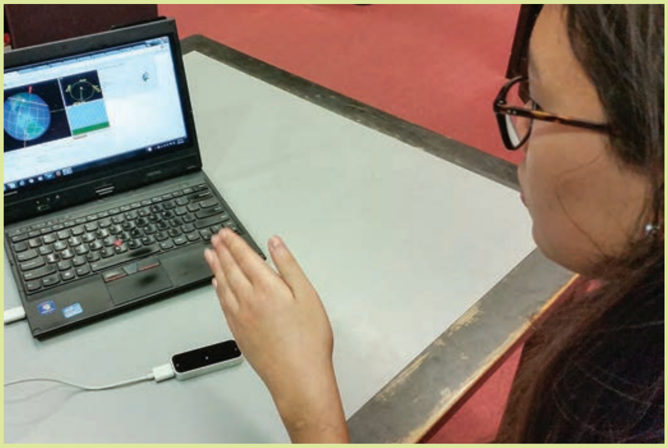

Figure 3b. The gesture input device, the Leap Motion controller, senses the angle the student's hand makes with the tabletop. By rotating her hand, she can control the sun's angle, and, therefore, the orbit of the Earth. To make a complete orbit, students must carefully consider how the sunlight angle changes or reverses for each season for different points on Earth.

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Our three emerging gesture-based simulations—molecular heat transfer in solids, the pressure-volume gas law relationship, and the causes of the seasons—are being tested with students using a similar interview format. The interview protocol still requires that students explain their evolving ideas, but attention is now focused on students' interaction with the simulations to assess how well students can control them and what they notice and learn. These interviews also include "challenges" where students are asked to use gestures to affect some change in the simulation and to describe what they think their gestures represent and what effect they have on the system.

To control the heat transfer simulation (Figure 1), students are able to select with their right or left hand one of two different blocks of molecules that represent solids. Depending on the rate at which they shake their hand, students can directly manipulate the vibrational speed of the molecules, thereby changing their temperatures. Students can see how the oscillations are transferred by the collision of molecules as the system equilibrates.

For the gas laws simulation (Figure 2), the central learning objective is the cause of pressure—that gas molecules in an enclosed vessel hit the surfaces harder and more frequently as pressure increases. In some of our early interviews, students represented pressure with the fingers or fist of one hand as molecules striking the other palm, as noted above. We are now testing this controlling gesture in the simulation, so that increased pressure decreases the volume that encloses that gas. This is a kind of reverse causality: generally, we think of decreasing the volume of a gas to increase the pressure. But our approach highlights the mechanism of pressure as the rate of the beating of molecules. Our seasons simulation (Figure 3a) uses a similar reverse causality to look at the angle of sunrays hitting the surface of the Earth as the major cause of the seasons. Here, we use the angle of a tipped hand to represent the sunray's angle, which controls the Earth's orbit (Figure 3b).

Our goal is to test the effectiveness of these and other gesture-based approaches to interacting with simulations of scientific phenomena. We hope to emerge with new insights for the field of embodied cognition and its direct application to new learning environments.

LINKS

GRASP
http://concord.org/grasp

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Monday's Lesson:

Can You Filter Your Water?

By Carolyn Staudt and Melinda Daniels

Although improved water supply and distribution are two of the great engineering achievements of the 20th century, the National Academy of Engineering lists "access to clean water" as one of its current worldwide challenges.* Addressing this challenge requires inspiring the next generation of scientists, engineers, and citizens to tackle clean water issues.

In the United States, this challenge is generally part of the civil infrastructure of drinking water and wastewater treatment systems. However, this infrastructure is aging and needs investment and enhancement, requiring political and economic leadership, research and development, and technological innovation. The recent case in Flint, Michigan, has brought national attention to this challenge.

Elementary through secondary students should understand the complexity of local and global water issues as well as the science and engineering of water projects and related careers. They need to be able to evaluate questions such as: How serious is the water challenge? In what ways do human actions affect water systems? How do we measure water quality? What technologies provide clean water?

In the Water SCIENCE (Supporting Collaborative Inquiry, Engineering, and Career Exploration with Water) project funded by the National Science Foundation (NSF), middle school students from southern Arizona, southeastern Pennsylvania, and eastern Massachusetts investigate local water resources through hands-on science and engineering activities, guidance from undergraduate and graduate student mentors, online interaction with STEM professionals, and learning about careers in environmental conservation and engineering. Student activities reflect the real-world challenges faced by water authorities: water scarcity and hardness in Arizona's arid climate, animal waste and agrochemical pollution in Pennsylvania's farming communities, and road runoff and wastewater management in the densely populated urban centers of eastern Massachusetts.

Collaborating in iSENSE

Students visualize their Water SCIENCE data in iSENSE, a free, interactive instructional website for collecting, sharing, and visualizing scientific data, co-developed by Machine Science and the University of Massachusetts Lowell and funded by NSF. Teachers and students from different schools can explore data from other classes or from a trusted outside source.

Try it out

In the "Can I filter my water?" activity (https://authoring.concord.org/activities/3028), students filter dirty water. Following the Design-Build-Test engineering process, they evaluate natural water filtration materials, design and build a stackable water filter, and test the effectiveness of their designs.

1. Create dirty water by adding potting soil, water-based clay, oil, vinegar, and garlic powder (for odor) to clean water.
2. Fill and label four clear plastic cups with different filter materials (e.g., sand, activated carbon, cheesecloth, coffee filter) (Figure 1).
3. Using a pin or scissors, punch small holes in the base of the cups so water can pass through them.
4. Insert two pushpins into opposite vertical sides of each cup, high enough so water will not leak out.
5. Sketch the design, deciding how to stack the filters in a gravity-driven filtration sequence.
6. Prime the system with clean water, then run dirty water through the filters.
7. Evaluate results by assessing reduction in water turbidity and odor.

Additional hints and background information are available in the teacher guide: https://guides.itsi.concord.org/water-science-teacher-guides

Sign up for a free account on the Innovative Technology in Science Inquiry portal (https://itsi.portal.concord.org) to create classes, assign this and other Water SCIENCE activities to your students, and view their work.

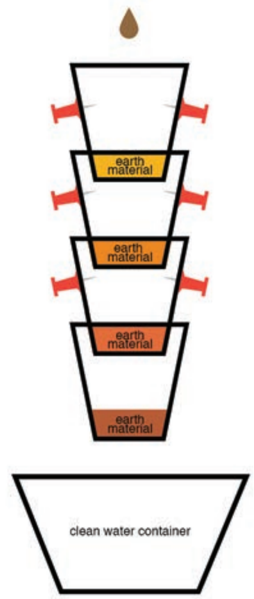

Figure 1. A stackable filtration system using different filter materials

LINKS

Water SCIENCE
http://concord.org/water-science

iSENSE
http://isenseproject.org

* See National Academy of Engineering Grand Challenges for Engineering (http://www.engineeringchallenges.org)

Can a Robot Help Students
Write Better Scientific Arguments?

By Trudi Lord and Amy Pallant

What if students were able to get immediate feedback on their open-ended responses in science class? Could that dramatically enhance their ability to write scientific arguments? A new project is exploring these questions by investigating the effects of technology-enhanced formative assessments on student construction of scientific arguments.

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The High-Adventure Science: Automated Scoring for Argumentation project is funded by the National Science Foundation in collaboration with the Concord Consortium and the Educational Testing Service (ETS). HASBot ("HAS" from the High-Adventure Science Earth science curriculum and "Bot" from robot for the automated nature of the feedback) uses an automated scoring engine to assess students' written responses in real time and provide immediate feedback (Figure 1).

HASBot is powered by the ETS automated scoring engine, c-rater-ML, which uses natural language processing techniques to score the content of students' written arguments. The c-rater-ML platform was integrated into two High-Adventure Science curriculum modules, "What is the future of Earth's climate?" and "Will there be enough fresh water?" In each module, students encounter eight scientific argumentation tasks, in which they use evidence from models and data to construct scientific arguments.

Each argumentation task is designed as a four-part item set, including: 1) a multiple-choice claim, 2) an open-ended explanation, 3) a certainty rating on a five-point Likert scale (from very uncertain to very certain), and 4) an open-ended rationale for the certainty rating. Previously, students would have to wait until their teacher had read their responses to get feedback. Students now get just-in-time feedback that encourages additional experiments with the models, a closer look at the data, and the opportunity to add more evidence and reasoning to their explanations. The goal of the feedback is to help students build stronger scientific arguments.

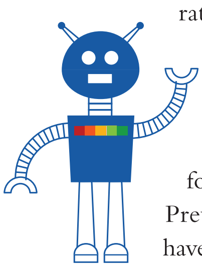

Figure 1. The HASBot robot provides automated, non-judgmental feedback to students' written responses.

Preparing for launch

Automated scoring is based on rubrics that differentiate student responses into five categories for explanations and five for certainty rationale, and includes feedback that is specific for each category (Table 1). Developing automated scoring models for the open-ended questions requires a large number of human-scored student responses. Fortunately, we have thousands of such human-scored responses from years of HAS implementations of the climate and water modules. Two project staff members scored these student responses independently. The reliability between the two human coders was excellent, ranging from 0.82 to 0.95 in kappa (k). Kappa is a statistic that represents inter-rater agreement ranging from -1 (less than chance agreement) to 1 (exact agreement).

The next step was to divide the human-scored data into two parts: a training set and a testing set. Approximately two-thirds of the data were used to train c-rater-ML, which generated a scoring model for each open-ended response argumentation task. The remaining data were then used to evaluate the computer-generated scoring model.

When a test set of responses was run through the c-rater-ML models from the training set, human-machine score agreement was between 0.70 and 0.89 k, which is an acceptable threshold for instructional purposes. In half of the items, however, the human-machine agreement was more than 0.10 k lower than the human-human agreement.

While it is not surprising that human-human agreement was higher than human-machine agreement, we were pleased with these initial results. We hypothesize that a lack of student responses on the higher end of the rubric may explain some of this variability, and that as student arguments improve with the use of HASBot's formative feedback, we will be able to retrain the c-rater-ML models with a wider range of responses and improve the accuracy of the automated scoring.

HASBot's mission

The four-part argumentation item sets were organized into a block that requires students to answer all four items before submitting their responses for scoring. C-rater-ML then analyzes students' written responses to the explanation and certainty rationale and returns numerical scores. After students submit their answers, the HASBot robot appears, prompting students to review their scores, displayed on a rainbow bar along with feedback, and inviting students to revise their answers (Figure 2).

We piloted the color score and feedback features in the spring of 2015 and were curious whether students would embrace, reject, or question the validity of the automated feedback. Students liked receiving feedback from HASBot because it was instantaneous and allowed them

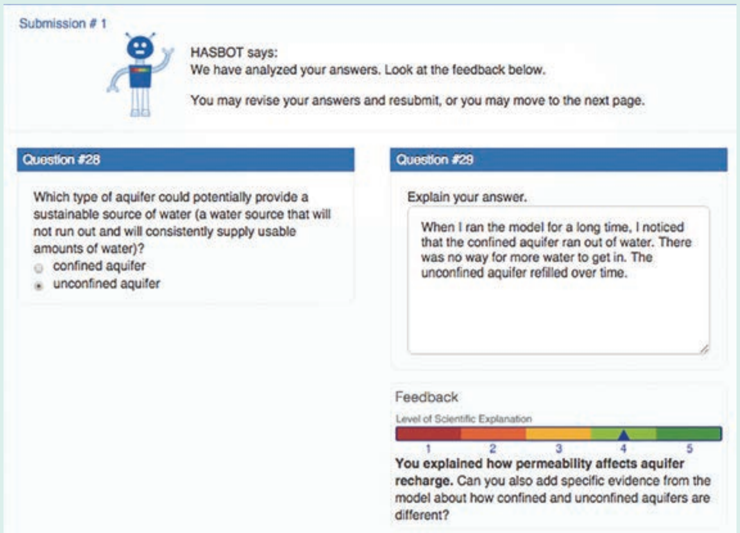

Figure 2. HASBot provides students with a score and contextualized feedback.

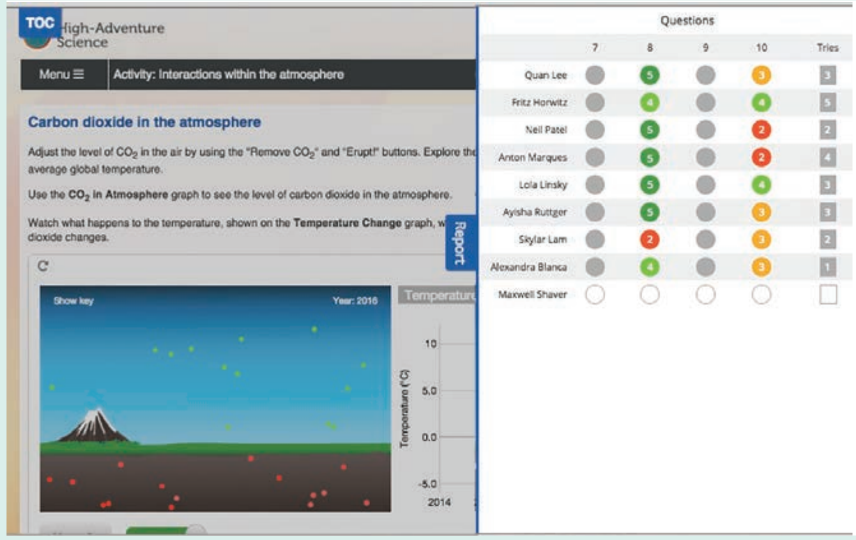

Figure 3. The teacher dashboard shows student scores using the same rainbow color scheme.

the opportunity to improve their answers. As one student aptly noted, "robots are non-judgmental."

In the first year of classroom implementation, students have generally responded positively to the feedback. Log files and student screencasts (in which we record student actions on the computer as well as their voices) reveal that students frequently revised their arguments based on HASBot's feedback, some of them many times. One teacher reported that her students "were surprised to get a score of 2 or 3. So it was a bit humbling for students, but they edited their answer and were determined to get a higher score. Success!"

One student said that automated feedback "teaches me to pay close attention to detail and how to correctly fix my mistakes." Another felt the feedback would help him "become very good at answering questions with justified reasoning." However, several students wanted more specific feedback with details on their mistakes and explicit hints to improve their answers.

We are currently creating and testing contextualized feedback to point students towards more specific ways to improve their arguments. We will test this feature in classrooms in spring 2016, and further refine our design based on the results of each classroom study.

Navigating into the unknown

In our quest to help students improve their scientific arguments, we have not abandoned teachers. They must also navigate the new world of automated scoring. We have developed a dashboard to help teachers keep track of student progress in real time. Before HASBot, teacher reports were limited to viewing student responses after class in a report separated from the activity. With the new dashboard, teachers can see their students' responses to the argumentation items in real time while students are still in the classroom (as well as after class).

A table of contents tab shows the location of students in the activity. On pages with an argumentation item set, a report tab shows student scores for each open-ended question using the same rainbow color scheme students see (Figure 3). Teachers can drill down into the report to see each individual student's responses to the argumentation item sets or an aggregated view of all responses to a particular item. We will pilot the new teacher dashboard in a small number of classrooms this year.

Looking toward the future

We will refine c-rater-ML scoring models, HASBot feedback, and the teacher dashboard based on data from ongoing classroom implementations. Reactions by both teachers and students have been promising and we are cautiously optimistic that automated scoring and feedback can play a central role in helping students develop the practice of scientific argumentation. With HASBot as our co-pilot on this journey, our goal is to discover the best ways to use enhanced technological tools to improve science learning.

Score	Meaning	General feedback to student
1	Off-task or non-scientifi answer	You haven't explained your claim. Look again at the pictures/models.
2	Student repeated claim	You made a claim without an explanation.
3	Student made associations	Your explanation needs more details.
4	Student used data or reasoning	You used evidence from the pictures/models or explained why this phenomenon happens.
5	Student used data and reasoning	You used evidence and reasoning.

Table 1. Detailed scoring rubrics differentiate student responses into five categories for explanations and assign a color code to each score.

LINKS

Automated Scoring for Argumentation
http://concord.org/automated-scoring-argumentation

High-Adventure Science
http://has.concord.org


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Supporting Secondary Students

in Building External Models to Explain Phenomena

By Dan Damelin and Joe Krajcik

Modeling, a central practice used in all science disciplines, is essential to the pursuit of scientific knowledge. Scientists develop, revise, and use models of relationships between variables to provide a predictive or causal account of scientific phenomena; engineers build models to test and revise design solutions. *The Framework for K-12 Science Education* and the Next Generation Science Standards (NGSS) identify modeling as one of eight science and engineering practices. Indeed, students should engage in modeling to learn and use the same practices scientists and engineers regularly employ. However, there are few tools designed for students to easily construct models, so there is little research on how the use of a modeling building tool could affect the way students develop conceptual frameworks related to scientific phenomena.

Supporting Secondary Students in Building External Models is a collaborative project with Michigan State University and the Concord Consortium, funded by the National Science Foundation (NSF) to examine how to support secondary school students in constructing and revising models to explain scientific phenomena and design solutions to problems. External models are both concrete and visible to others, and may appear as a set of equations, a qualitative description of mechanisms, or a simulation. A mental model, on the other hand, refers to an internal, private framework of concepts used to represent an individual's understanding of some phenomenon or design solution. The purpose of both types of models is to explain what we see and predict what we will see next. The central tenet of the project is that increased student engagement with external models leads to measurable improvements in the quality and sophistication of students' conceptual understanding as represented by their internal models.

Introducing SageModeler

To build robust mental models, students need easy-to-use tools with which they can design, test, share, and discuss representations of these models. The centerpiece of this environment is a systems modeling tool. There are many types of models, but a significant number of phenomena are best represented using systems models. By constructing a systems model to represent a mental model, students can then test the outcome of their assumptions—what factors to include and how relationships between those factors produce a certain behavior or outcome.

We are developing a new web-based systems modeling tool—SageModeler—based on the MySystem concept mapping tool developed at the Concord Consortium, and on Model-It, a systems modeling tool developed by Elliot Soloway, Joe Krajcik, and their colleagues.* Our goal is to scaffold student learning so that young students, beginning in middle school, can engage in systems thinking at earlier stages in their conceptualization process.

Students can use SageModeler as a simple diagramming tool, then—with pedagogical support from teachers and a curriculum that supports modeling—specify relationships between factors. Defining these relationships as words (for instance, "as factor *a* increases, factor *b* increases by the same amount") relieves students of complex math, and allows them to focus on understanding simple relationships between variables (Figure 1). We will also make it possible for more mathematically sophisticated students to construct models that later can be refined using algebraic definitions, and extend the modeling features to include a traditional systems dynamics modeling approach.

Developing a robust mental model that has explanatory and predictive power occurs through a process of designing, testing, and refining external models. As with almost all dynamic model development, scientists compare the results of the model with some external data set in order to

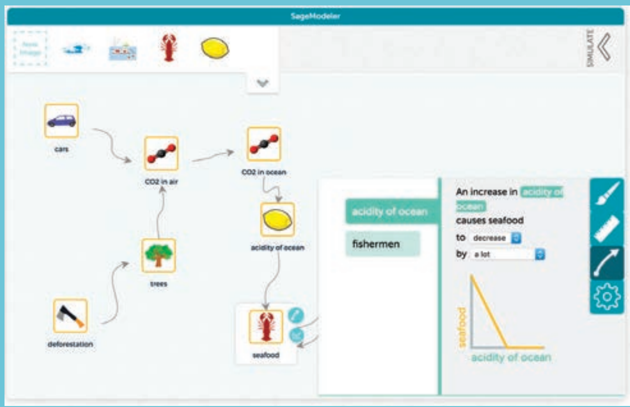

Figure 1. SageModeler can use words and pictures of graphs to set relationships between variables, making it possible for students to create a runnable model without the need for writing equations.

Figure 2. SageModeler embedded in CODAP allows for data analysis even when using semi-quantitative values and functions. Notice where the graph axes are "low" to "high" and how the table uses bars to represent relative values.

better understand a system and improve their models. To facilitate iterative development based on data analysis, SageModeler is embedded in CODAP, the Common Online Data Analysis Platform (Figure 2). CODAP is an intuitive graphing and data analysis platform that takes the outputs from the systems models, as well as any other data source—published data sets, such as ocean temperatures or CO_2 emissions, results of computational models like Next-Generation Molecular Workbench or NetLogo, or data from sensors—and combines them into a single analytic environment.

Instructional units

We will design, develop, and test several short project-based learning units that support students in developing and using models. Each unit will last approximately two to three weeks and will engage students in constructing models to explain phenomena and in revising their models to better fit comparison data.

Designed for the middle grades, our first three-week unit (Why do fishermen need forests?) introduces students to several aspects of the carbon cycle, focusing on transfer of carbon dioxide between the atmosphere, hydrosphere, and biosphere. Students create, test, evaluate, and revise their own models while exploring the concepts of carbon sequestration by trees, deforestation, transfer of carbon dioxide between the atmosphere and hydrosphere, ocean acidification and its effect on calcifying species, photosynthesizing species, biodiversity, food webs, and human nutrition and economy.

The instructional materials align with the NGSS to engage students in three-dimensional learning by using crosscutting concepts (systems and systems modeling, cause and effect, and energy and matter) with various scientific practices (particularly modeling, but also analyzing and interpreting data and engaging in argument with evidence) and disciplinary core ideas. The materials support students in building an understanding of the performance expectations from NGSS.

Research

Our research plan explores the effect of student-constructed external models on the development of their internal mental models or conceptual understanding. We propose that when students build external models, they develop connections among ideas, creating a network of ideas in their conceptual understanding. As students engage in the modeling process their understanding evolves and the framework of ideas that forms their conceptual understanding changes. New expressions of this understanding are demonstrated by a refinement of their systems model, forming a feedback loop between engagement with building external models and the development of a conceptual understanding.

We will examine the quality of student-created models, the potential of these models to provide feedback on students' understanding of a range of disciplinary core ideas, and the development of students' modeling capabilities. Our goal is to increase students' science learning by constructing external models and to explore student engagement with modeling as a scientific practice. For curriculum designed with this goal in mind, we believe SageModeler can help students engage in one of the most fundamental practices of science—building models to explain and predict phenomena—while developing more complex and nuanced understandings of scientific phenomena.

* Metcalf-Jackson, S., Krajcik, J., & Soloway, E. (2000). Model-It: A design retrospective. In M. Jacobson & R. Kozma (Eds.), *Advanced designs for the technologies of learning: Innovations in science and mathematics education*. Hillsdale, NJ: Erlbaum.

LINKS

Building Models
http://concord.org/building-models

SageModeler
http://concord.org/building-models/sage-modeler

The Challenge
of an Open-Ended Design Challenge

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is a learning scientist.

By Jie Chao

During China's notorious three-day national college entrance exam you hear prayers everywhere. My life—indeed, every high school student's life in China—would be different following the exam, or so we were told. The physics test was on the hottest day. A couple of useless fans sputtered above, pitying us. I swept through the test and felt good—until the last question. After reading it three times, my heart was pounding and my brain was numb. The question included a complex machine I had never seen. Decompose and find the equations, I told myself. Divide and conquer. I scribbled all over the margins, yet the solution kept falling apart. The clock was ticking.

The answer eventually arrived—in time. I suspect it was a matter of luck or, perhaps, my hobby of doodling helped to model the bizarre machine. The door to my dream college was opened, but life afterwards was far from a smooth sail. At every step, I stumbled. That last physics question always came up. I wish I had learned to be comfortable with novelty, complexity, and uncertainty.

Energy3D

In the spring of 2015, the Big Data project, funded by the National Science Foundation, brought our Energy3D software, a simulated engineering design environment (SEDE), to freshmen physics classrooms. Students designed energy-efficient homes and city blocks, and the challenge was nontrivial. Students had to understand the science of thermodynamics, the impact of the sun's path, and functions of various building materials. They had to assess the pros and cons and complete the design project under budget. There were hundreds of decisions to make.

(Your students can try this design challenge, too! See "Monday's Lesson: Designing an Energy-Plus Home" in the fall 2015 @*Concord* and http://energy.concord.org/energy3d/projects.html.)

The project is multidisciplinary and invites design thinking and spatial skills. There is no direct instruction, no correct answer, and no explicit guidance. Adults deal with things like this all the time. But high school students?

On the first day, one student noted, "They [the solar panels] are on the level of 10% [solar panel efficiency], because I do not totally understand what the solar panel scale means. I put the Solar Heat Gain Coefficient to 80%. Once again, I don't understand what the numbers mean." Later in the design process, she complained several times, "I'm stuck. I'm seemingly so close to the efficiency level I need to achieve, but the changes I make don't seem to make much of a difference at all."

Near the end, she still struggled: "I put in solar panels and made sure that the windows were covered by trees. The problem with making a colonial house is that the walls and roof were extremely expensive. My area was towards the smaller side, but balancing the amount of windows against the energy efficiency was extremely difficult. I never got below a 5000 net energy." She reminded me of exam day: the searching, failing, and rising to try again.

What was so challenging about this design challenge?

A concept map of green building science

The concept map of design elements and science concepts (Figure 1) provides an overview of the energy-efficient home design challenge. As illustrated with arrows between nodes, a building's energy performance is determined by numerous factors embedded in a complicated interdependent web. For instance, the highlighted nodes represent the subsystem of solar panels. To optimize the performance of solar panels, students need to consider multiple factors including orientation, surface area, solar conversion rate, shade by surrounding objects, etc. Changing one factor may cause a chain of effects and create unforeseen repercussions on the final outcome.

With no trail to follow, how do students move through this complex web of design elements and science concepts? Thanks to Energy3D's powerful logging engine, we are able to capture students' moment-by-moment design actions as well as the intermediate states and energy performance of their designs. Combining these data streams and plotting them over time provides a window into their mental processes throughout the design project.

Another student, a quiet and conscientious girl who started with little knowledge in this subject, attained the largest learning gain. How did she do it? Figure 2 [s1-s8] shows her solar panels' performance (kWh/panel) over time during the first design. Although the overall trend was positive, there were many fluctuations and some performance drops that canceled out previous improvements. Why did she keep regressing? If she found a way to improve the average energy generation, why didn't she stick with the solution? The design snapshots below the time graph shed some light on her seemingly erratic design behavior.

Initially, she put 32 panels of 10% solar conversion rate all over the oddly shaped roof [s1]. She was rather unconcerned with them until their performance declined significantly due to the tall trees she planted around the house [s2]. However, instead of moving the trees, she opted to reshape her roof so the panels could face south [s3]. This move boosted the panels'

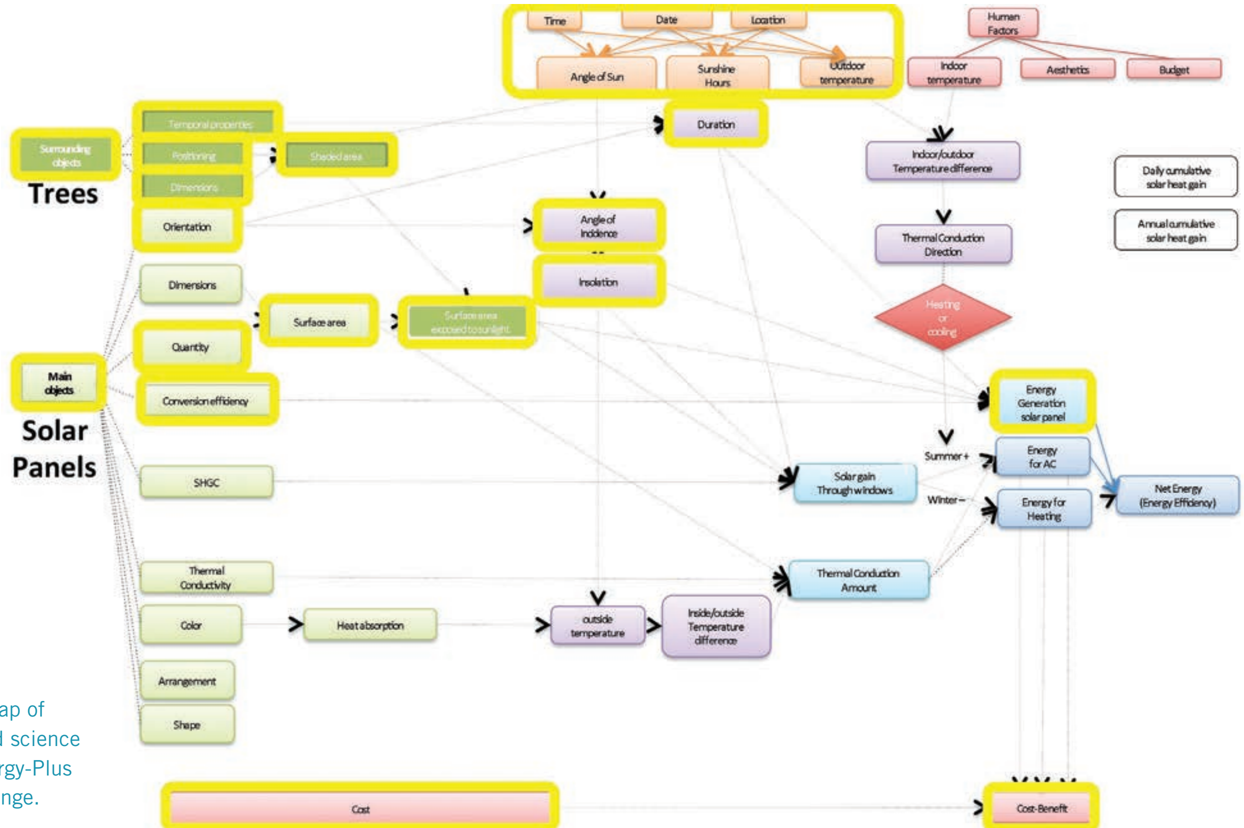

Figure 1. Concept map of design elements and science concepts in the Energy-Plus Home Design Challenge.

performance, but she still missed the critical factor—the tall trees. She may have used the trees to provide shade in the summer to save on air conditioning costs. Later, she moved the trees even closer to the house, further compromising the solar panels' performance. Rather than addressing the problematic shade from the trees, however, she made a pyramid roof and added up to 59 panels to increase energy generation. She then realized that only 40 panels were allowed in the design specifications [s4].

After 20 minutes, her design changed completely. We cannot be sure what she was thinking, but the trees were gone, and 40 panels were neatly lined up on the south, east, and west sides of the house [s5]. The panels' performance peaked. Just a few minutes later, she planted eight tall trees on the westside, possibly compelled by the desire to include some landscape features in her design [s6]. Soon she realized this was not a good move and removed the trees and replaced 12 panels with higher conversion rate [s7]; she also moved some panels to the south-facing roof [s8]. In the end, she found a solution for the first design, and she continued to improve her solar panels' performance in two additional designs with ease. There was a lot of back and forth, but her discoveries served her well.

Watching her design path was painstaking. I could hardly refrain from helping. But years from now, even if she's forgotten how to design an energy-efficient house, she may remember the perplexing situation she was in, the discomfort she felt, and the perseverance that ultimately paid off.

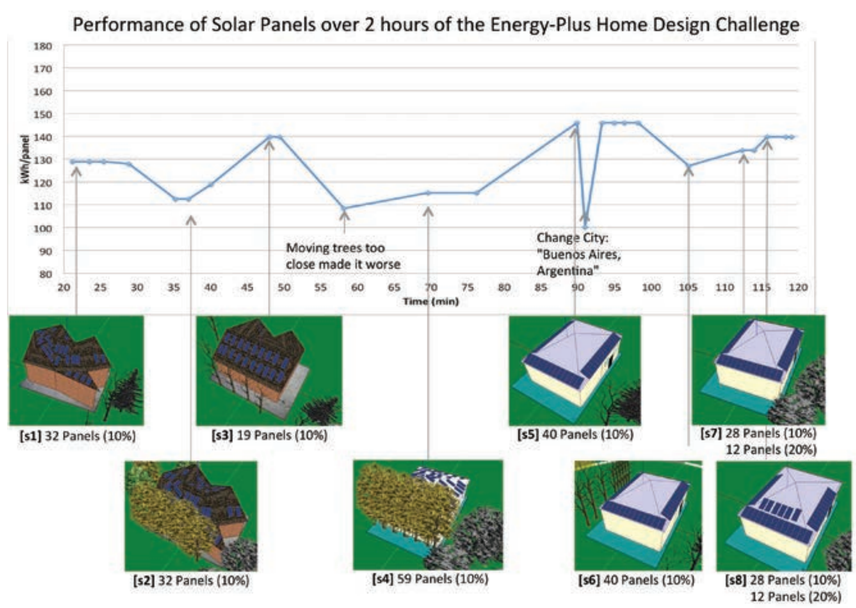

Figure 2. Performance of solar panels over two hours of the Energy-Plus Home Design Challenge.

LINKS

Big Data
http://concord.org/bigdata

Under the Hood:

Creating Multi-User Activities with Firebase

Sam Fentress
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By Sam Fentress

In educational technology research, we increasingly see the value of connecting users to collaborate on a difficult problem or to compete against each other in a game. Our Teaching Teamwork project, funded by the Advanced Technological Education program at the National Science Foundation, is investigating the use of online collaborative activities for evaluating the contribution of individual team members as they work together to solve simulated real-world electronics problems on separate computers linked by the Internet.

Since we already had an existing stand-alone online circuit simulator from a previous project, our goal was to add real-time collaboration capabilities to connect users' breadboards as part of a team activity. We looked for the fastest, easiest way to connect users together and found the perfect tool in Firebase, a real-time, NoSQL cloud database. Firebase stores data as JSON documents, which can be jointly edited by multiple users. With just a few lines of JavaScript, our browser-based activities connect to the database and create or modify data.

Now we can represent the entire state of the shared application as a single shared document. As each user's version of the application modifies parts of the JSON, the whole document is updated in real time for each user's screen, much like several people editing a Google Doc.

Teaching Teamwork players must each modify their own part of a larger shared circuit in order to generate the correct output. Because one user's actions on his or her breadboard affect another part of the circuit for a teammate, team members must communicate to share goals and strategies. By simply placing the entire circuit state in the shared JSON file, and allowing users to modify only their own portions, each user's representation of the complete circuit gets updated any time one of their collaborators changes a component or interacts with his or her breadboard (by changing a resistor or lifting a lead to break the circuit, for example).

Take a look at the code. We have a (trivial!) circuit with two resistors, which

```
Circuit JSON, shared on Firebase
{
 "battery": {
   "voltage": 9,
   "connections": "1, 2"
 },
 "resistor-a": {
   "resistance": 100,
   "connections": "2, 3"
 },
 "resistor-b": {
   "resistance": 100,
   "connections": "3, 1"
 }
}
```

we represent in JSON. Each user can only modify the value of their own resistor, but each time their partner makes a change, their own representation of the circuit is updated. Both users' applications agree on the new state of the circuit, and any calculations made, such as voltmeter readings, are updated in real time.

The ease with which we can set up multi-user interactions has let us add this quickly in places where we might not have chosen to invest time building server applications. For example, we created a shared High Score Board in one day for our Genigames project in which users breed dragons to learn about inheritance patterns and developed a multi-user electrical grid management game for our Learning Everywhere initiative. Even in projects that eventually move to their own custom server-side applications, being able to create multi-user apps in a matter of hours allows us to iterate rapidly on new ideas to foster collaboration in student learning.

```
In our JavaScript app
var firebaseRef = new
Firebase("<YOUR-APP-URL>"),
    myResistor = "resistor-a";

// this is called once to
// initialize the circuit, and
// again any time a change is
// made.
firebaseRef.on("value",
function(circuitState) {
  setCurrentCircuitState(
    circuitState);
});

// call this any time the user
// updates their own resistor,
// to update the shared circuit
function updateResistor(newValue)
{
  firebaseRef.child(myResistor).
     set({
       "resistance": newValue
     });
}
```

LINKS

Teaching Teamwork
http://concord.org/teaching-teamwork

Firebase
http://firebase.com

Innovator Interview:

Jie Chao

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Q. When you tell other people what you do, what do you say?

A. I'm trying to figure out what learning will look like in the future and how learning can shape that future. I'm interested in getting students to do authentic, relevant projects. I use learning analytics and data mining to help me understand student learning.

Q. How did you come to educational technology?

A. I'm very proud of my university, but education in China is really frustrating. I majored in chemistry but didn't get into labs until my final year. That was too late. I had skipped so many lectures to go mountain climbing. I stumbled into an educational services company after graduation and became interested in the science of learning and teaching. I applied to the University of Virginia Instructional Technology program and have been passionate about learning sciences and pedagogy ever since.

Q. How does your background play into your philosophy about education?

A. I struggle with the contrast between American and Chinese education. One is very liberal with little emphasis on facts and the other puts too much emphasis on facts and not on active learning. I lean towards the active learning camp, which is a more powerful way to incorporate new knowledge, though it brings challenges for educators because everyone is different. That's where computers come in—we can build a big sandbox where everyone can learn on personalized and productive tracks.

Q. What's been interesting about the Mixed-Reality Labs project?

A. Mixed-Reality integrates the power of computer simulations with sensors to enhance science learning. Simulations are effective learning tools in many ways, but they cannot replicate many unique affordances provided by labs with physical materials. Kids like to touch things. When you experience reality, you're not speaking with the software creator—philosophically, you're speaking with God. It's right there, but it's mysterious. We wanted to marry these two. We use sensors to take data from physical labs and drive simulations in real time. We also use sensors to generate direct effects on simulations. Finally, we use infrared cameras to look at reality through IR imaging.

An IR camera is a great tool to support inquiry. When you see the moon with a telescope, you ask about the dark spots. If you don't see them, you never ask the questions. Similarly, IR adds sensing abilities, making it natural to ask questions. It's easy to imagine bringing IR imaging into augmented reality like wearable glasses. Students could then do experiments and see physical reality with six or seven senses!

Q. How do you use learning analytics?

A. Our Energy3D data is so rich, it almost replicates the classroom, though I'm drowning in data. The ability to collect data at such a fine grain size is like having a new sense for asking questions and looking for patterns. Currently, we're looking at three high-level design categories—construction of prototypes, analysis of student design, and reflection on the design process. We've used cluster analysis to explore different types of effort allocation in these three design activities. Similar techniques are also used for analyzing profiles of explored design space, analytic space, and design episodes. We'll apply sequence-matching techniques to enable machine recognition of design behaviors. There's a lot to explore.

Q. Tell us about your first year at the Concord Consortium.

A. I've loved it! I've learned so much from everyone, especially Charles [Xie]. He is such a visionary thinker and hands-on doer. And our research forum gives me a great window to see what everyone is doing. I'm excited about all the potential for collaboration here.

The Concord Consortium

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New Support for Learning Everywhere Initiative

The Concord Consortium is pleased to announce the second phase of a revolutionary $2 million initiative using technology to bridge informal and formal STEM learning experiences. The generous support of the William K. Bowes, Jr. Foundation and the JPB Foundation launches the next phase of our Learning Everywhere initiative and expands an existing partnership with the New York Hall of Science (NYSCI).

Technology has fundamentally changed our everyday life, and it offers great potential to help learning experiences transcend physical boundaries. One area especially primed for such transformation is the informal learning that takes place in museums. Museums provide access to phenomena on an inspirational scale, creating environments filled with powerful emotional and sensory experiences. However, museum experiences remain fragmented and solitary, suffering from the "Vegas problem"— what happens in the museum stays in the museum.

Our Learning Everywhere initiative is working to address this issue by bringing Concord Consortium researchers and developers together with the designers and researchers behind NYSCI's groundbreaking Connected Worlds exhibit, which immerses visitors in a set of fantastical animated and interconnected worlds, from rainforests to deserts, in which their actions—gestures, movements, and decisions—affect how the worlds are kept in balance. We'll forge new ground in creating learning experiences that span informal and formal learning settings, and use cutting-edge technology to track learners' actions both within and across these settings, analyzing these actions to understand how to foster coherent, extended learning. We aim to connect museum and classroom experiences and make opportunities for such learning available to the wide diversity of learners and social groups who visit museums.

Fathom™ Dynamic Data Software

Fathom is dynamic software that's fun and effective for teaching data analysis and statistics. It's also a powerful tool for high school students to use for modeling with mathematics, as required by the Common Core State Standards. In addition to helping students understand algebra, precalculus, and statistics, Fathom's powerful data analysis capabilities make it an excellent tool for the physical and biological sciences, as well as for social science courses. Fathom is widely used for data exploration and analysis in grades 8–14. The award-winning Fathom is now available at reduced prices—from just $5.25 per copy (or less for multiple copies), a savings of up to 40%. Get your copy today at fathom.concord.org.

High-Adventure Science Partnership with National Geographic Education

We are excited to announce that our High-Adventure Science modules are now available as a collection on the National Geographic Education website (education.nationalgeographic.org/high-adventure-science), thanks to a National Science Foundation-funded partnership. We welcome the opportunity to share these modules with a wider audience of middle and high school teachers and students. All modules continue to be available on the High-Adventure Science website (has.concord.org).

Each week-long module is built around an important unanswered question in Earth or environmental science, and includes interactive computer models and real-world data. Students attempt to answer the same questions as research scientists, though we don't expect them to be able to arrive at definitive answers. The goal is to engage students in the process of doing science, building arguments from evidence and data, and realizing that uncertainty drives scientific progress. Our research has shown that, after using High-Adventure Science modules, students improve both their understanding of scientific content and argumentation skills.

Partnering with National Geographic Education allows us to provide more support for teachers. On their website, you'll find in-depth teaching tips, background information, vocabulary definitions, links to standards, and links to related resources in the National Geographic catalog.

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