@CONCORD

vol.23 • no.1 • Spring 2019

The Concord Consortium
CELEBRATING 25 YEARS
concord.org

Perspective:

25 Years of Innovation and a Glimpse into the Future

By Chad Dorsey

The Concord Consortium was founded on a single, grand vision: technology would one day transform the way we learn science, mathematics, and engineering. A quarter century later our vision is playing out in classrooms and homes around the world. From supporting novel investigation to opening up modeling and data exploration, technology makes sense-making possible in ever more powerful ways. New frontiers in analytics, collaboration, artificial intelligence, and other technologies deepen and expand possibilities for STEM learning and open the door to long-term continued innovation.

This founding vision, launched by Bob Tinker 25 years ago, grew out of a convergence of forces. Moore's Law, which maintains that computer processing power doubles every year, correctly forecast decades of exponential innovation. As personal computers started appearing in homes and schools, people recognized they were useful beyond the office. In its early days the Internet was available to only a few, but its potential became apparent quickly. And miniaturization introduced a new genre of truly mobile devices that would grow into today's powerful smartphones.

These factors represented a perfect storm of innovation that would come to revolutionize learning. Early progress at the Concord Consortium proceeded in multiple directions, each powered by a different combination of these innovations. Pairing an Apple II microprocessor with a Polaroid camera's auto-focus sensor or a basic two-wire thermistor yielded the world's first motion detector and a new family of fast-response temperature sensors, which would help decades of learners visualize phenomena in new ways. Combining computer availability with global networking gave rise to the nation's first online high school and a network supporting the first online teacher professional development. Linking specialized research computing algorithms to the power of microprocessors made modeling and simulation possible for pedagogical purposes, unlocking entire worlds of scientific exploration into otherwise-inaccessible concepts such as molecular interactions and plate tectonics.

We have always believed that computing would become ubiquitous, that powerful modeling and simulation tools would be widely used, and that mobile devices would unlock the power of information and data for everyone. And in many ways, they finally have. We take for granted that our mobile devices can provide computationally modeled weather forecasts, instantly calculate precise financial projections, or visualize astronomical occurrences in real time. Yet even as we enjoy the benefits of this technology revolution, there is more work to be done. Society must ensure we make the best possible use of technology in education—to extend and deepen STEM learning in meaningful ways for all learners.

New technologies and new possibilities

New technologies seem to appear daily, bringing with them the potential to transform the ways we teach and learn. Miniaturization has moved beyond mobile phones to supply a flood of devices in all conceivable forms. This new landscape, powered by tiny microcontrollers and storage devices, now supports a burgeoning ecosystem of innovation from everyday household devices to drones, monitoring technologies, and robotic devices. This Internet of Things (IoT) has transformed industry, business, and medicine in countless ways, tightening supply chains, providing new opportunities in security, and revolutionizing longstanding medical procedures. Yet the potential IoT holds for education remains largely unexplored.

Through our research, we are learning how to use IoT devices for pedagogical purposes, identifying new applications and modes of use. We're helping students deploy sensors and actuators to automate independent, long-term biology investigations. We're helping learners engineer solutions, and studying how these tools interact with mobile computing platforms to assist learning. And we're employing these devices across a wide variety of situations, from citizen and community science to hands-on maker projects. We're excited about what the Internet of Things offers STEM education, and we're working with promising applications to explore ways they can build student understanding of computing and computational thinking.

Another essential, though almost transparent feature of technology today is collaboration. With boundless opportunities to connect with others, we often assume that collaboration is a given. However, while examples of collaborating around technology

Chad Dorsey
(cdorsey@concord.org)
is President of the Concord Consortium.

As we look forward to the next 25 years and consider the new innovations to come, we remain optimistic and confident that technology's role in STEM learning will continue to expand.

have long been available, true and deep exemplars of collaborative technology for enhancing STEM learning remain elusive. We are paving the way in this regard, experimenting with modes and methods by which technology can connect learners. Whether building workplace-ready collaboration skills in electronics troubleshooting or bringing middle school students together to build a joint understanding of mathematical concepts, we're opening new possibilities for learning with collaborative technology.

Artificial intelligence (AI) is yet another area in which technology has come into view recently. While it incubated quietly in academia for decades, always seeming just a few years away, in the past ten years it has finally begun to deliver on its longstanding promise. Having proven out its feasibility, AI has gone on to rapidly find application in healthcare, engineering, entertainment, and industry—sometimes appearing seemingly everywhere one looks. AI and machine learning have the potential to revolutionize learning as well. Whether reframing the way learners approach engineering in open-ended problems, assisting them in improving their argumentation skills, or helping teachers identify and focus on students' most critical sense-making needs as they progress in game-based learning, we are working to advance exemplars of AI's important possibilities within STEM education.

New opportunities, longstanding need

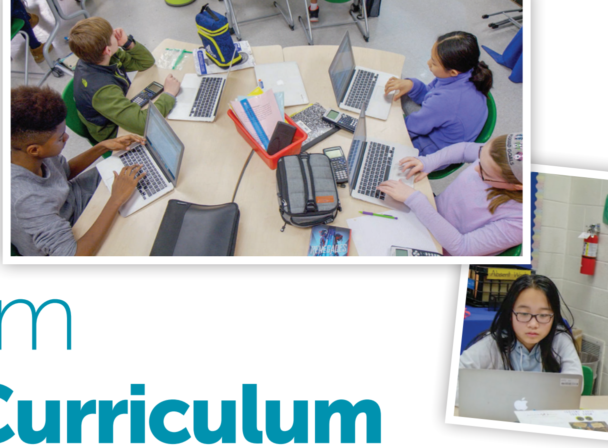
There's no doubt it's an exciting time to be in science teaching and learning. The new perspectives introduced in *A Framework for K-12 Science Education* and adopted by the Next Generation Science Standards (NGSS) and many state standards usher in a new paradigm for science learning. Teachers nationwide are beginning to embrace the central tenets of NGSS: downplaying memorization, emphasizing students' ideas, and engaging learners in actively making sense of phenomena.

It is not a simple shift. In many ways it upends decades of traditional science teaching and means rethinking long-held assumptions about learning. Nonetheless, educators across the nation are learning to adopt new methods and approaching their students' thinking in novel ways. This seems like cause for celebration, and it is. It also creates exciting new challenges. In order to bring about deep, rich STEM understanding, learners must be able to engage firsthand in the practices of science, mathematics, and engineering. For many topics, this is eminently possible. Hand lenses, stopwatches, pendulums, balances—as well as plain old dirt, water, and patience—all offer countless avenues for investigation of the surrounding world, generally limited only by teachers' readiness and imagination. However, a great many STEM topics do not make themselves so readily available, and few give up their mysteries easily. Instead, the wonders of the world must be actively teased out. In many such cases, phenomena are invisible, or data are messy and overwhelming, or key concepts lie within highly complex, interacting systems. In these and many other cases, technology is critical to honing STEM practices and discovering and understanding STEM concepts across topics.

Our work at the Concord Consortium is focused on these situations—places where technology opens up worlds that are otherwise closed off for learning. In far too many STEM subjects, learners are still deprived of important opportunities to act and think like scientists. Technology often holds the key. As we look forward to the next 25 years and consider the new innovations to come, we remain optimistic and confident that technology's role in STEM learning will continue to expand. We see a future where more learners have the freedom every day to comprehend the invisible structure and beauty of the world around them while building skills and confidence in investigating and answering important questions.

Designing a Digital Collaborative Mathematics Classroom

Using a Problem-Based Curriculum



By Leilah Lyons, Elizabeth Phillips, and Chad Dorsey

Leilah Lyons
(llyons@nysci.org) is an Associate Professor of Computer Science and the Learning Sciences at UIC, and Director of Digital Learning Research at the New York Hall of Science.

Elizabeth Phillips
(phillip6@msu.edu) is a senior academic specialist in the Program in Mathematics Education at Michigan State University.

Chad Dorsey
(cdorsey@concord.org) is President of the Concord Consortium.

For nearly three decades, the Connected Mathematics Project (CMP) has worked to design, develop, field test, evaluate, and disseminate student and teacher materials for mathematics classrooms. CMP was developed as a complete three-year, problem-based middle grades curriculum. CMP has been used by thousands of students across all 50 states and in many international schools, and has received multiple awards and accolades, including exemplary status by the U.S. Department of Education's Mathematics and Science Education Expert Panel.

Since its initial publication in 1996, the goal of CMP has been to create a classroom environment that supports students' mathematical development through the process of exploring, conjecturing, reasoning, communicating, and reflecting. When mathematics is embedded in contextual problems, the challenge for teachers is to pay attention to students' problem-solving strategies, help them make the mathematics visible, and connect the embedded mathematics learning to prior and future understandings.

One of the key features in a CMP classroom is collaboration. Students and teachers actively work together on important and challenging mathematical tasks. In the Launch phase, the teacher connects the context to prior knowledge and describes the challenge. During the Explore phase, students work together to solve the problem as the teacher moves around the classroom observing, prompting, redirecting, questioning, and encouraging. Students make and validate conjectures, consider alternative strategies, question each other, and communicate their findings. In the Summarize phase, the teacher and students share, solidify, clarify, validate, generalize, connect, and extend their understandings.

New possibilities for CMP: Digital collaborative environments

While extensive research on CMP has shown increases in both student and teacher learning and dispositions towards mathematics, CMP authors continue to seek ways to enhance student and teacher learning. A recent grant awarded by the National Science Foundation to the Concord Consortium and Michigan State University explores new possibilities for CMP classrooms. The goal of the Digital Inscriptions project is to leverage the unique affordances of technology for 21st century learners and develop a digital collaborative CMP classroom that enhances student learning of mathematics. Could we build a "living" textbook where social and carefully structured math learning can promote true disciplinary engagement?

While envisioning a living textbook for today's learners, we were inspired by STEM disciplines that focus on problem-solving, critical thinking, and collaboration. We wanted to promote learning that resembles the work of STEM professionals, so we redesigned the CMP problem format to more closely align with a STEM environment. The *Initial Challenge* contextualizes the problem while *What if…?* provides the opportunity to make the embedded mathematics visible. Students take ownership of their learning in *Now What Do You Know?* as they connect their learning to prior knowledge and consider future payoffs. The CMP STEM problem format for the digital environment continues to support the Launch/Explore/Summarize phases of the lesson (Figure 1). This framework also helps teachers address the challenge of teaching mathematics when the mathematics is embedded in problem contexts.

We also considered how to integrate the potential of digital media into existing CMP classroom practices. The new platform includes the following features.

Digital feature 1: Embedding student workspaces and mathematics tools into the textbook

In the CMP curriculum, learners immediately engage in doing mathematics within a situating challenge. The digital platform immerses learners in problem-solving that begins with the *Initial Challenge* and continues throughout the unit, culminating with students understanding key mathematical ideas embedded in the unit. To support a smooth transition to problem-solving, each problem has an embedded workspace adjacent to it. Elements of the problem (text, images, graphs, tables, etc.) can be dragged into the workspace where they are converted into special-purpose, interactive "tiles" that can be rearranged (Figure 2). Students have access to embedded digital tools to solve the problems, including tools for writing text and creating tables, images, drawings, and graphs. This flexible workspace allows students to dive into the problem using resources suggested by the problem, as well as other tools, to develop their own solution strategy. According to one student, "At my age people understand technology better than other things. Some people can't draw and some people can't write as well, but with technology it's easier for everyone to type and draw with the computer."

Digital feature 2: Transforming prior problems into reusable artifacts to support future work

As learners transition from the Launch phase of the problem to the Explore phase, they solve problems and scenarios by connecting and building on mathematical ideas they have developed when solving earlier problems. In the software adaptation of CMP, students can revisit workspaces from prior problems to review older artifacts and copy-paste them into new workspaces. This helps learners "remix" the mathematical formalisms they have used in the past, combining, for example, an equation developed in an *Initial Challenge* with a graph that uses the equation to solve a new *What if…?* problem. The reusable artifacts make concrete the CMP design principle that as learners encounter new situations in which they use mathematical reasoning, skills, and procedures, they make connections to ideas they have already encountered.

Digital feature 3: Transforming the textbook into a safe, shared collaborative workspace

What distinguishes experts in a domain from novices is not necessarily the amount they know, but the speed and accuracy with which they match what they know to the needs of the situation. CMP design guidelines state it this way: "knowing how to, but not when to, is not sufficient" for developing mathematical conceptual and procedural understanding. Far too often, students learn mathematics as a recitation of form. When given a problem framed in a particular way, they faithfully execute the solution steps by rote. Knowing what framing to use, however, is core to understanding. Novices can be "trapped" in their preconceptions about how to view a problem. Exposure to the thought processes of others can be helpful. In paper and pencil CMP classrooms, teachers adopt strategies, such as jigsawing, to help students "cross-populate" ways of thinking about a problem. Seeing a variety of ways to solve the same problem, learners are better able to attend to (and develop versatility with) problem framing, fundamentally changing their notion of what it means to "do" mathematics from mere process execution to a metacognitive level of mathematical reasoning.

One way the digital platform supports learners' ability to flexibly frame problems is in the design of a "parallel awareness" view. When learners log in, they are assigned to groups of four. While working on problems in their individual workspaces, each learner accesses the so-called "four-up" view, which juxtaposes the learner's workspace with those of the other three group members (Figure 3). At the click of a button, students can share their own work and see what their partners are doing in real time. They can also copy artifacts created by their teammates. One student remarked, "I can drag other people's work and graphs into my workspace to help me solve the problem in a better way." At

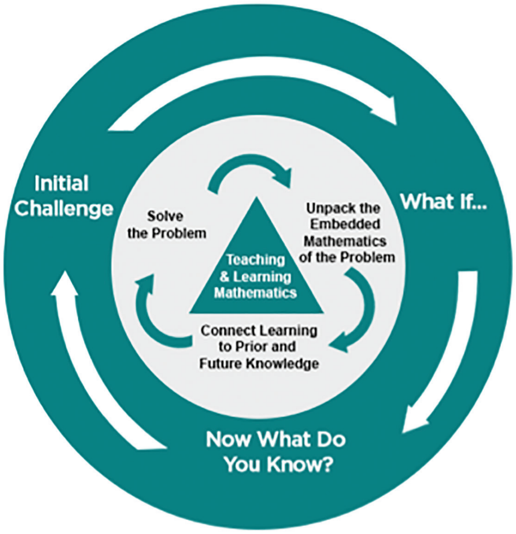
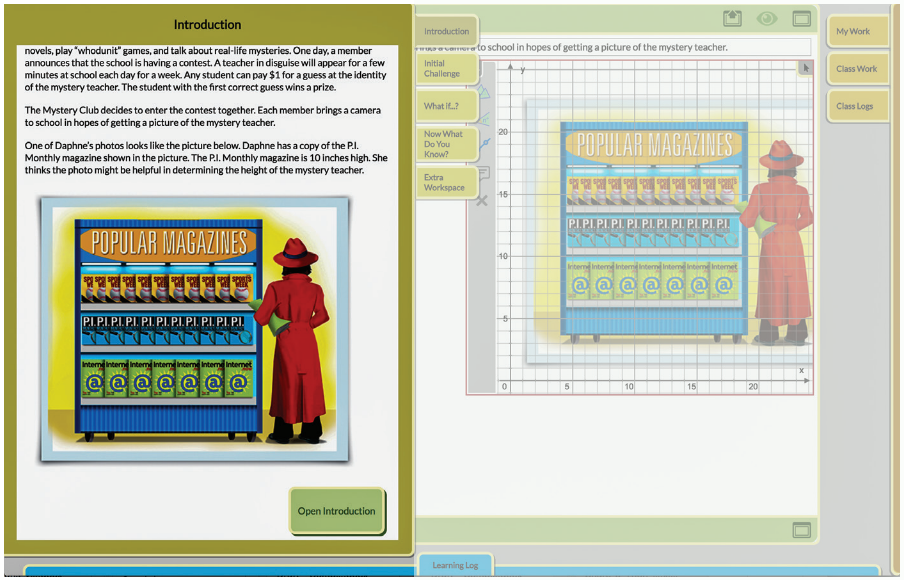


Figure 1. The three phases of the CMP instructional model (inner circle) supported by the three sections in the STEM problem format (outer circle).



novels, play "whodunit" games, and talk about real-life mysteries. One day, a member announces that the school is having a contest. A teacher in disguise will appear for a few minutes at school each day for a week. Any student can pay $1 for a guess at the identity of the mystery teacher. The student with the first correct guess wins a prize.

The Mystery Club decides to enter the contest together. Each member brings a camera to school in hopes of getting a picture of the mystery teacher.

One of Daphne's photos looks like the picture below. Daphne has a copy of the P.I. Monthly magazine shown in the picture. The P.I. Monthly magazine is 10 inches high. She thinks the photo might be helpful in determining the height of the mystery teacher.

Figure 2. Elements of the problem can be dragged into the workspace where they are converted into interactive "tiles." Each tile supports a different tool: text, table, image, drawing, and graph.

(continued on p.6)

(continued from p. 5)

the same time, this student was glad to share work she had done, noting, "It feels good when a student uses my work to help them on their own problem because it feels like I'm doing something for someone else, even though I'm just doing my own work." Students can discuss strategies and assign parts of the problem to individuals, and then combine their strategies into a complete solution that can be shared with the class.

Being privy to one another's problem framing, learners reflect on which approaches to the solution make the most sense. They revise their own strategies to use the best ideas, and practice the metacognitive skill of evaluating and choosing a problem frame. Another student said, "I can share my work and then I can talk to my partner and we can both get our ideas together to get one solid answer." And according to the teacher, "If they're stuck I often see them turn to the person next to them and say, 'Turn on your sharing screen. Look at my screen and see if that gives you some ideas.'" She continues, "It's safer than before when they would have to ask, 'Can I see your notebook?' It felt more like cheating when they were doing it paper and pencil. On the computer they're comfortable letting each other see their work or share it."

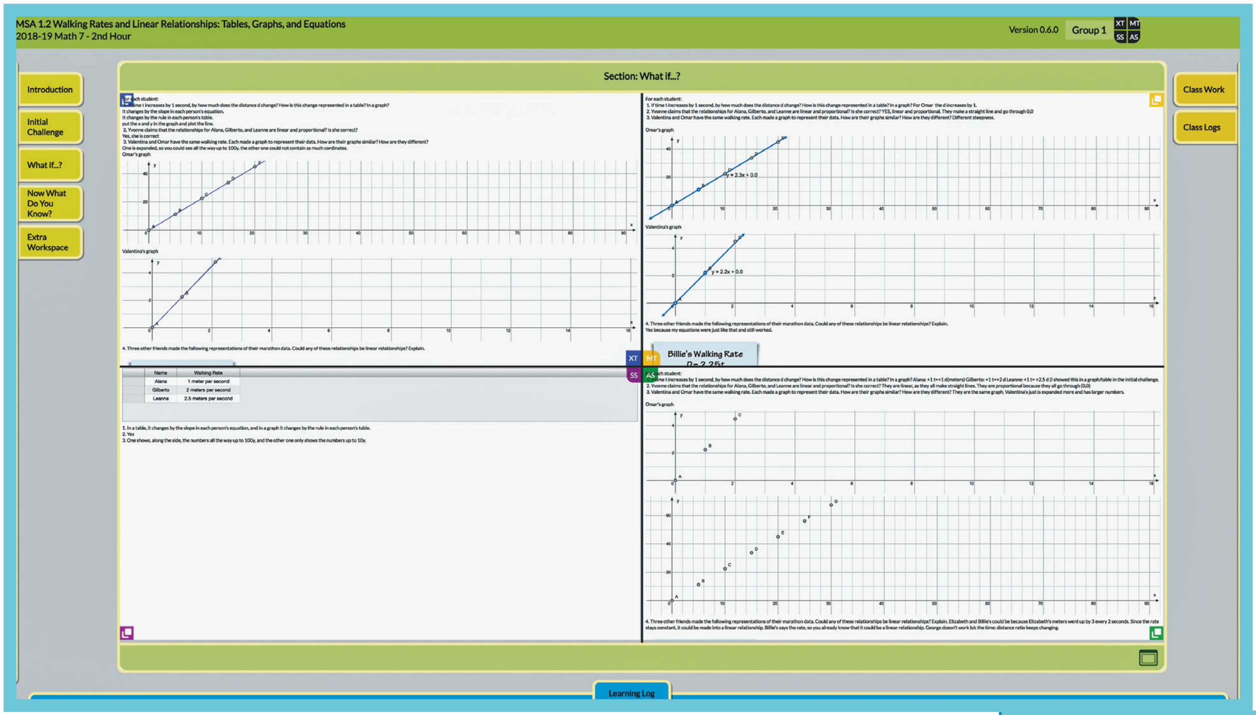
Digital feature 4: Extending and connecting the lifespan of concepts from textbook units

Reusable digital artifacts are more than a convenience. They allow learners to reuse concepts. During the Summarize phase, the class as a whole reviews and consolidates concepts, using the *Now What Do You Know?* question(s) as a prompt. The idea is that the classroom distills their shared knowledge into artifacts they can easily refer back to in future units, or even in future years of the curriculum. This allows learners to distribute their practice over time, helping them reach a level of fluency in familiar and unfamiliar situations, allowing them to make connections to other concepts and procedures. The digital environment consolidates concepts by streamlining the process of collecting, revising, and combining mathematical artifacts in a separate area intended to record crosscutting ideas, concepts, and procedures: the Learning Log. Students can copy tiles from curriculum materials, problem workspaces, the workspaces of classmates or the teacher, or prior Learning Log entries, and edit them to best capture the concept. They use these entries to pull together ideas into the sort of repurposable formalisms that make mathematics so useful. Learning Logs persist across problems and units, and potentially across academic years, allowing learners to revisit, reuse, and refine their mathematical insights throughout the CMP curriculum.

Mathematics for a social classroom

The new CMP digital platform builds on the strengths of the CMP classroom system, with its rich artifacts and culture of shared knowledge building, and re-envisions how collaborative teaching and learning in mathematics can be best supported. Placing artifacts at the center of students' experience and making them readily accessible to all fosters idea sharing in ways that have never been possible before.

During the project's pilot phase, the expressive and collaborative possibilities of this new platform have generated new insights among teachers who have taught with CMP for years. One teacher enthused, "Our students are used to being social on technology, so why not use those skills in our classrooms and allow them to be social on a technology about what they're learning." Making the textbook "come alive" is more than just making it interactive, it also makes it socially alive, integrated into the social fabric of the classroom.



For each student:
ime t increases by 1 second, by how much does the distance d change? How is this change represented in a table? In a graph?
It changes by the slope in each person's equation.
It changes by the rule in each person's table.
put the x and y in the graph and plot the line.
2. Yvonne claims that the relationships for Alana, Gilberto, and Leanne are linear and proportional? Is she correct?
Yes, she is correct
3. Valentina and Omar have the same walking rate. Each made a graph to represent their data. How are their graphs similar? How are they different?
One is expanded, so you could see all the way up to 100y, the other one could not contain as much cordinates.

4. Three other friends made the following representations of their marathon data. Could any of these relationships be linear relationships? Explain.

	Name	Walking Rate
	Alana	1 meter per second
	Gilberto	2 meters per second
	Leanne	2.5 meters per second

1. In a table, it changes by the slope in each person's equation, and in a graph it changes by the rule in each person's table.
2. Yes
3. One shows, along the side, the numbers all the way up to 100y, and the other one only shows the numbers up to 10y.

For each student:
1. If time t increases by 1 second, by how much does the distance d change? How is this change represented in a table? In a graph? For Omar the d increases by 1.
2. Yvonne claims that the relationships for Alana, Gilberto, and Leanne are linear and proportional? Is she correct? YES, linear and proportional. They make a straight line and go through 0,0
3. Valentina and Omar have the same walking rate. Each made a graph to represent their data. How are their graphs similar? How are they different? Different steepness.

4. Three other friends made the following representations of their marathon data. Could any of these relationships be linear relationships? Explain.
Yes because my equations were just like that and still worked.

ch student:
ime t increases by 1 second, by how much does the distance d change? How is this change represented in a table? In a graph? Alana: +1 t=+1 d(meters) Gilberto: +1 t=+2 d Leanne: +1 t= +2.5 d (I showed this in a graph/table in the initial challenge.
2. Yvonne claims that the relationships for Alana, Gilberto, and Leanne are linear and proportional? Is she correct? They are linear, as they all make straight lines. They are proportional because they all go through (0,0)
3. Valentina and Omar have the same walking rate. Each made a graph to represent their data. How are their graphs similar? How are they different? They are the same graph, Valentina's just is expanded more and has larger numbers.

4. Three other friends made the following representations of their marathon data. Could any of these relationships be linear relationships? Explain. Elizabeth and Billie's could be because Elizabeth's meters went up by 3 every 2 seconds. Since the rate stays constant, it could be made into a linear relationship. Billie's says the rate, so you already know that it could be a linear relationship. George doesn't work b/c the time: distance ratio keeps changing.

Figure 3. The parallel awareness or "four-up" view juxtaposes the learner's workspace (upper left) with those of the other three group members.

LINKS

Digital Inscriptions
https://concord.org/digital-inscriptions

Integrating **Computational Thinking** in STEM

By Jie Chao

Jie Chao
(jchao@concord.org)
is a learning scientist.

The depth and complexity of societal, environmental, and economic problems facing our nation and the globe increasingly demand computational solutions. But the principles of computing need not be relegated to computer science courses. Integration with STEM subjects offers an enticing path for bringing computing to many students.

In 2006, Jeannette Wing wrote that computational thinking is "a fundamental skill … every human being must know to function in modern society."* Thirteen years after this seminal article, computational thinking (CT) finally is making its way into K-12 classrooms, thanks in part to the Next Generation Science Standards and the Common Core State Standards. The Concord Consortium is developing innovative technologies and unique research agendas across several projects to help students engage in computational thinking. The goal is to create opportunities for students to do science and use math in the same ways professionals do, using the power of computational thinking to solve real-world problems.

Biology and chemistry students are using our SageModeler systems modeling tool to create computational models of complex phenomena and iteratively uncover underlying mechanisms. Budding meteorologists are building weather models using embedded phenomena and a NetLogo modeling environment to systematically incorporate important variables and simulate impacts on human activities (see "A Virtual Storm Teaches Computational Thinking" on pages 12-13). In biology classrooms students are creating systems to monitor and control experiments using open-source Internet of Things sensors with Dataflow, a flow-based programming tool (Figure 1). In Earth science classrooms students are designing dynamic visual maps to simulate and assess natural hazards and risks using GeoCoder, a visual programming platform for geoscience. And with our math modeling learning platform CodeR4MATH, math modelers are applying math and data science with the R programming language (Figure 2).

In these projects, we're creating computer interfaces to help students translate their ideas to computational models. As a result, students can leverage CT concepts such as decomposition, abstraction, and algorithmic thinking to further their thinking about science and math concepts. And teachers can pursue ambitious pedagogies that potentially lead their students to the frontiers of STEM learning.

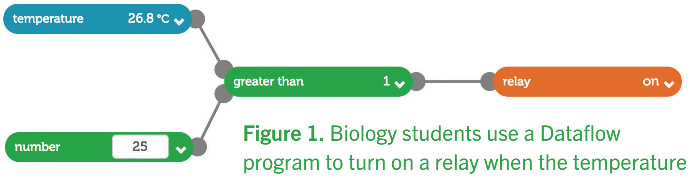


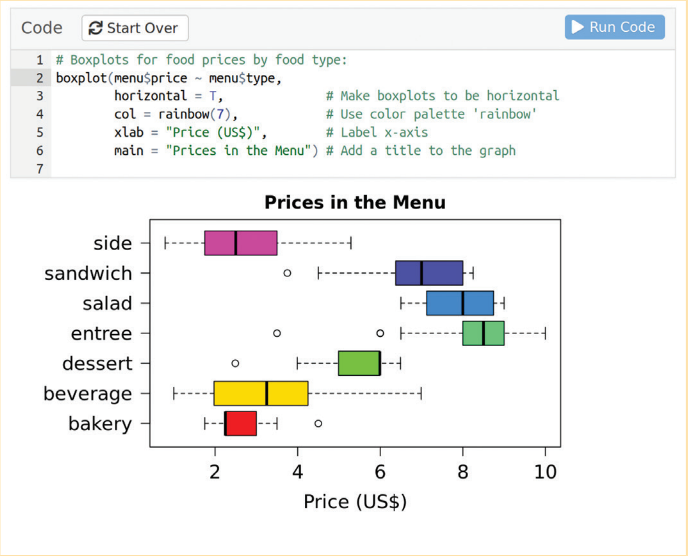
Figure 1. Biology students use a Dataflow program to turn on a relay when the temperature is above 25 degrees in a mini-biome.

Research

Our research into computational thinking is also investigating forward-looking questions. Research on explanation, argumentation, agency, and learning trajectories is enriched and informed by embedding and investigating CT in novel learning environments.

We are inquiring how students explain multi-level, complex phenomena with a visual display of their thoughts and experimental results. We are asking how students interpret spatial-temporal phenomena such as weather events across a classroom. We are using a sociocultural perspective to explore how students develop agency—a sense of ownership—while they tinker with computational artifacts. We are investigating how uncertainty-infused scientific argumentation is enriched with a reciprocal computational thinking cycle, which draws ideas from and generates evidence for the argumentation cycle. And we are designing and testing pathways for learning multiple complex skills such as math modeling, computer programming, and computational thinking, simultaneously and synergistically.

The challenges we have taken on with these ambitious projects are both exciting and humbling. We're shaping the future of education, starting with fostering the computational thinker in every student.



```r
# Boxplots for food prices by food type:
boxplot(menu$price ~ menu$type,
        horizontal = T,              # Make boxplots to be horizontal
        col = rainbow(7),            # Use color palette 'rainbow'
        xlab = "Price (US$)",        # Label x-axis
        main = "Prices in the Menu") # Add a title to the graph

```

Figure 2. Students create math models using the R programming language.

---

*Wing, J. (2006). Computational thinking. *Communications of the ACM*, 49(3), 33-35.

Why Everyone Can and Should be a Scientist

By Colin Dixon

Colin Dixon
(cdixon@concord.org)
is a research associate.

Imagine an eighth grade student climbing down a bank to a creek near her school every day of her summer vacation. She stops at the water's edge to carefully take a sample in a 5 ml test tube. She analyzes the water along with friends and a few members of a senior center, who have joined her group to gather additional samples. They identify pollutants and add their data to an online database. These data help tell the story of dirty water that needs attention. Restoration work along the creek is under way and, prompted by the data the group has compiled, the city government has begun conducting additional monitoring for sewer leaks and illegal dumps.

Now imagine a pollution meter installed on the roof of an apartment building. Through an RSS feed, an eleventh grade student extracts and analyzes this data. He's determined to learn more about the causes of pollution. Inspired by his younger sister who plays soccer but has to stay inside when the air is bad, he creates a sculpture that displays the level of particulate matter and shares his artwork—and his data—at a community festival. Regional agencies have expressed interest in the data collected by this rooftop pollution meter to assess the impacts of traffic, weather, and fire on community health.

These are examples of citizen and community science (CCS), and the data collected and contributed by young and old, amateur and veteran, are critical. These data create a *mutual dependence* that makes CCS both scalable and meaningful; scientists benefit from data that would be difficult or expensive to collect, and students benefit by learning with scientists and contributing to authentic scientific work. CCS is more than "realistic" science, it is real science—a difference that has emotional, motivational, and cognitive consequences.

CCS encompasses many forms of science in which members of the public participate in the production of new knowledge used for resource management, community decision-making, or basic research. In *contributory* or *scientist-led* projects, a professional scientist has a specific question to answer and defined protocol to follow. These are typically known as *citizen* science projects. *Co-created* or *student-originated* projects start from a question or problem learners have identified. Such projects are more commonly thought of as *community* science. There is a wide spectrum of CCS projects with many degrees of collaboration and contribution.

Authentic science and identity

An emerging set of digital tools for producing, sharing, and analyzing data is now available for educational use. These can support the Next Generation Science Standards, which highlight the importance of authentic science and engineering practices, including asking questions and defining problems; planning and carrying out investigations; analyzing and interpreting data; and obtaining, evaluating, and communicating information. However, the development of scientific identities is equally important. Participation in authentic science can support the development of scientific identities by exposing learners to other critical aspects of science, including scientists' ways of communicating and thinking and a wide variety of careers and mentors in science. It also shows learners that science can serve many purposes, including those relevant to their communities. CCS can help develop learner agency by supporting engagement with unanswered, often messy, questions, and contributing to endeavors that extend beyond a report card.

Best practices for learning in CCS

The two ways of working with data described above—from direct water samples at a local creek to data collected from a rooftop pollution meter—are both possible in CCS thanks to tiny digital temperature sensors, real-time graphing, new Internet of Things sensors, collaborative digital sharing tools, and low-cost electronics. Of course, much can still be done with a clipboard and pencil. Across various forms and technologies, research has documented best practices for the most educational value from youth participation in CCS.

Support specialization

Science is done in teams, by team members with different levels and kinds of knowledge and experience. In CCS, some participants may take on more or different kinds of work than others. As they develop roles within a project, participants can see all parts of the process, even while they might specialize in particular aspects of scientific work—from conducting data analysis to checking data quality or designing materials for dissemination. These roles can help young people, especially those who are new to science, use existing identities and build from areas of expertise toward other practices of science.

Make scientific contributors visible

It is also important to make both professional and non-professional scientists visible by creating a direct connection to scientists, while acknowledging young people as legitimate contributors and local experts. To ensure that learners see that their work is valuable to others, students and citizens should have opportunities to present data and findings, from posters at scientific conferences to presentations at a town hall or research briefs on a community forum. Scientists should also ensure that participants understand how their data is being used to create new knowledge.

Create conversations

In both CCS and more traditional science education, young people often have few ways to share their ideas and expertise. CCS projects can go beyond scientific products and help participants share their work with family and friends in ways that feel relevant and exciting. Media and messages should encourage personal expression alongside scientific evidence.

Make a big deal of data

Data is the currency of science, and tools for producing, storing, accessing, and analyzing data make participation by all more powerful. Producing data is core to CCS, yet many projects move quickly to analysis and explanation as the focus of student reasoning. Conversations in the field and lab can bring to the surface questions about what counts as good data and how to describe the data for others who are looking at it secondhand. Creating datasets that capture observations and allow learners to answer local questions goes beyond formal protocols.

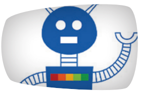
Provide opportunities for learner action

Connecting science to concerns, curiosities, and larger communities makes CCS meaningful. From organizing events to using research findings to advocate for policies to participating in restoration or other actions informed by the data, connecting CCS activities to local issues is critical when considering both the equity and ethics of science and science education. CCS is one small step to ensuring that science is accessible to all and reflects the questions and concerns of many.

Community and citizen science is more important than ever as a way to address climate change, species collapse, changing land uses, and other local and global concerns. CCS makes it clear that science is a collective endeavor, and that doing science is vital—and possible—for everyone.

Automated Scoring Helps Student Argumentation

By Sarah Pryputniewicz and Amy Pallant



Sarah Pryputniewicz
(spryputniewicz@concord.org)
is a research assistant.

Amy Pallant
(apallant@concord.org)
is a senior research scientist.

For the past four years, a robot avatar named HASBot has provided feedback to hundreds of middle and high school students on how to write strong scientific arguments. HASBot—a combination of High-Adventure Science or "HAS" and "Bot" as in automated scoring robot—came to digital life through the National Science Foundation-funded High-Adventure Science: Automated Scoring for Argumentation project. In partnership with the Educational Testing Service (ETS), we integrated HASBot into two curriculum modules in which students use models and real-world data to investigate issues related to humans and environmental sustainability.

In the "What is the future of Earth's climate?" module, we paired HASBot with eight argumentation item sets. Each item set consists of four parts: a multiple-choice claim, an open-ended explanation, a Likert scale certainty rating, and an open-ended certainty explanation. HASBot provided students with feedback on their typed explanation and certainty rationale responses.

Training HASBot

The ability to provide students with meaningful feedback on their open-ended written responses requires computers to "learn" from humans first. A computer needs to be "taught" the features of a good argument through a method of machine learning (ML) called natural language processing (NLP). This is not trivial and includes several steps for this process to work.

First we needed to identify the range of students' responses. During the six years of the High-Adventure Science project, dozens of teachers used the climate module with their students. We developed rubrics and scored between 1,200 and 2,000 scientific explanation and certainty explanation responses for each argumentation item set. As a result, we were familiar with the language students used to explain their claims and certainty ratings. Based on our knowledge of how students express themselves, we then developed a new rubric structure that would allow us to provide specific types of feedback.

To train the automated scoring models, the human-scored responses were input into c-rater-ML, an NLP system developed by ETS. The automated scoring models were compared to the human scores, and the algorithms were adjusted until the automated scoring model output matched human scores at least 70% of the time. Even though automated scoring is not perfect, it is good enough to provide students with timely, targeted, and consequential feedback to help them improve their arguments with data and reasoning.

In one of the climate module activities, students use a model to determine the effect of carbon dioxide on atmospheric temperature. Students add and remove carbon dioxide in the model and observe the interactions of solar and infrared radiation with carbon dioxide. Graphs of model outputs help students determine the relationship between carbon dioxide and temperature (Figure 1).

In the argumentation item set that follows the model, students make a claim about what happens to the temperature if all of the carbon dioxide is removed from the atmosphere. Students explain their claim, make a certainty rating, and describe what influenced their certainty. Each of these questions contains a hint about how to select a claim, the components that make up a good explanation, and factors that might influence one's certainty about a particular claim. After completing the argumentation item set, students submit their responses. Within four seconds, HASBot provides specific feedback on their explanation and certainty rationale responses.

The feedback is designed to complement the hints embedded in each question, helping students recognize the features of a complete scientific argument. After receiving feedback, students can edit their responses.

HASBot's feedback and one student's responses

Now let's follow one student, Tom, to see the role of HASBot's feedback in the modifications Tom makes to his explanation responses. When Tom submits his first response, he repeats his claim that the temperature decreases when carbon dioxide is removed from the model (Figure 2). He does not cite specific evidence from the model or any reasoning to explain why the temperature would decrease, so HASBot suggests he support his claim with evidence and reasoning. Tom receives a score for his scientific explanation in a rainbow bar. The bold text below the bar describes his score in a diagnostic statement, while the plain text includes suggestions for improving his argument. The feedback is different for each level of the scientific explanation rubric (scores 0 through 6).

Tom then edits his response and submits a second time, this time citing a positive correlation between the amount of atmospheric carbon dioxide and temperature (Figure 3). In response, HASBot recommends that Tom provide specific evidence from the model and graphs, as well as reasoning about greenhouse gas and solar radiation interactions to support his claim.

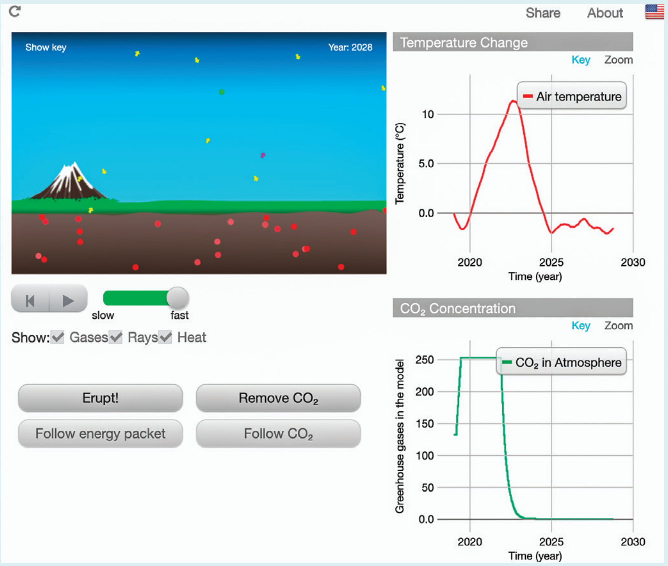
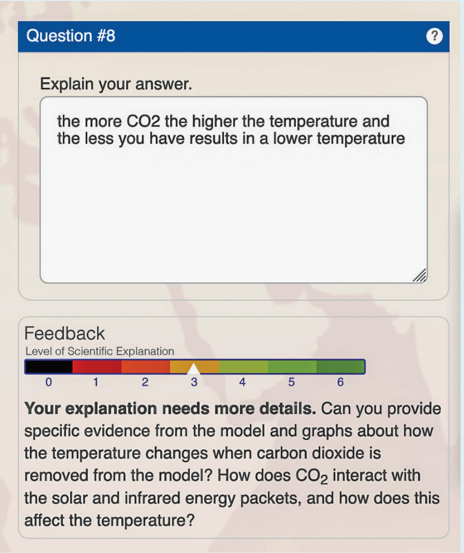


Figure 1. Climate model in which students determine the relationship between carbon dioxide and temperature.


Question #8

Explain your answer.

the more CO2 the higher the temperature and the less you have results in a lower temperature

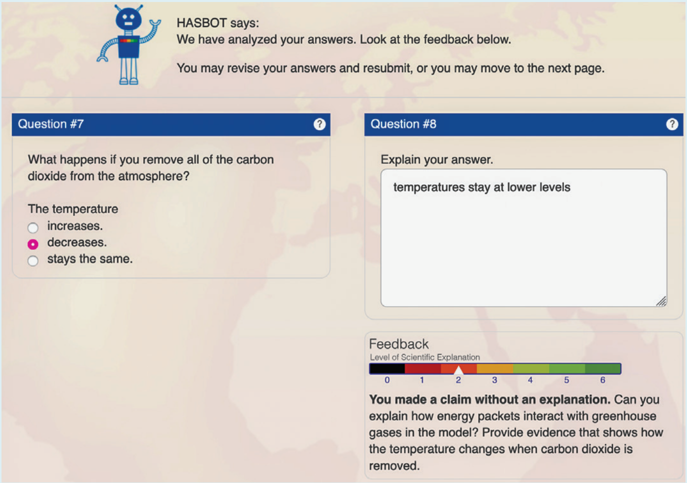
Feedback

Level of Scientific Explanation

Your explanation needs more details. Can you provide specific evidence from the model and graphs about how the temperature changes when carbon dioxide is removed from the model? How does CO_2 interact with the solar and infrared energy packets, and how does this affect the temperature?

Figure 3. The student's second submission of the explanation item. The claim item was unchanged.

Figure 2. A student's first submission, showing only the claim and explanation items. The question mark to the right of the question number provides a hint.


HASBOT says:
We have analyzed your answers. Look at the feedback below.

You may revise your answers and resubmit, or you may move to the next page.

Question #7

What happens if you remove all of the carbon dioxide from the atmosphere?

The temperature
○ increases.
● decreases.
○ stays the same.

Question #8

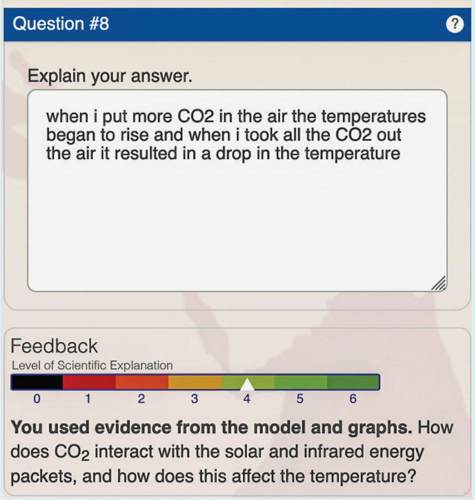
Explain your answer.

temperatures stay at lower levels

Feedback

Level of Scientific Explanation

You made a claim without an explanation. Can you explain how energy packets interact with greenhouse gases in the model? Provide evidence that shows how the temperature changes when carbon dioxide is removed.


Question #8

Explain your answer.

when i put more CO2 in the air the temperatures began to rise and when i took all the CO2 out the air it resulted in a drop in the temperature

Feedback

Level of Scientific Explanation

You used evidence from the model and graphs. How does CO_2 interact with the solar and infrared energy packets, and how does this affect the temperature?

Figure 4. The student's third submission of the explanation item.

When Tom modifies his answers for a third submission, he includes specific data from his experiments with the model, explaining that adding CO_2 in the model results in a temperature rise and removing CO_2 in the model results in a temperature decrease (Figure 4). This is an improvement, but it is not the most complete explanation possible. If Tom had included reasoning about why the temperature increases (the mechanism of greenhouse gas and radiation interactions), he would have received the highest scientific explanation score.

The explanation feedback is designed to encourage students to include both data and reasoning in the explanations of their claims. HASBot provides similar targeted feedback to students' certainty rationales, encouraging them to consider their certainty with the data and evidence that was presented.

The role of the teacher in providing feedback

While HASBot prompted Tom to modify his responses, the teacher must also be kept in the loop to help students make sense of the feedback and underlying scientific concepts. We developed a teacher dashboard that allows the teacher to quickly scan color-coded scores to monitor progress of the whole class. The teacher can see each student's scores and assess whether a student is improving over the course of one or more responses, or if a student is stuck on a particular score, perhaps because he or she is struggling with the science content or the more general understanding of claim, evidence, and reasoning. While HASBot is designed to help students, ultimately the teacher decides how to engage individual students or the entire class for a deeper discussion. Even a trained robot is no substitute for a classroom teacher.

LINKS

High-Adventure Science: Automated Scoring for Argumentation
https://concord.org/automated-scoring-argumentation

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

A Virtual Storm Teaches Computational Thinking

By Carolyn Staudt, Tom Moher, and Joyce Massicotte

Carolyn Staudt
(cstaudt@concord.org)
is a senior scientist.

Tom Moher
(moher@uic.edu) is an Emeritus
Associate Professor,
University of Illinois at Chicago.

Joyce Massicotte
(jmassicotte@concord.org)
is a project manager.

Few phenomena are as important to our daily lives as weather. We listen intently to reports of far-flung weather catastrophes and exchange updates about our local weather as a matter of course. Weather is no less important to children—a rained-out championship game or an unexpected snow day can be a major event.

Weather and weather forecasting offer an ideal medium for the integration of science, mathematics, and computational thinking. To predict the weather, meteorologists must understand data quality and sampling trade-offs, speak the language of computational models, and be able to clearly characterize the uncertainty of model predictions. It's no wonder that understanding weather is found throughout the Next Generation Science Standards from kindergarten through high school.

Working with Argonne National Laboratory, Millersville University, and the University of Illinois at Chicago, we are designing and testing instructional materials and technologies to promote eighth grade students' abilities to apply computational thinking practices and understandings in the context of weather and weather prediction. Funded by the National Science Foundation, the Integrating Meteorology, Mathematics, and Computational Thinking project (known as Precipitating Change) aims to empower students to understand and apply weather-related science and mathematics by employing computational thinking involving data and models.

An inquiry-based curriculum

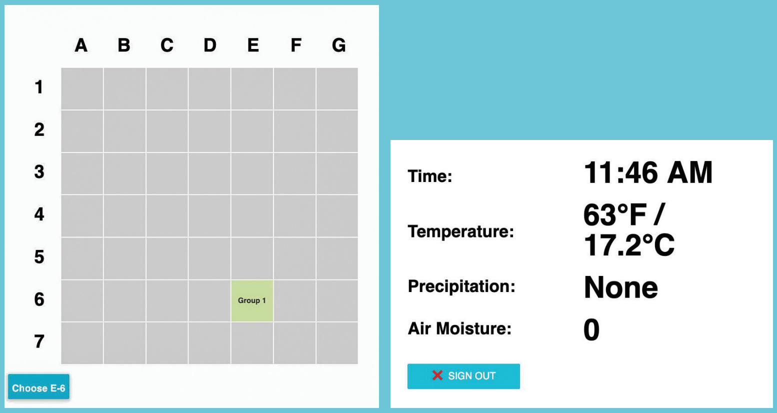
The Precipitating Change curriculum targets two main NGSS standards: MS-ESS2-5 (Collect data to provide evidence for how the motions and complex interactions of air masses result in changes in weather conditions) and MS-ESS3-2 (Analyze and interpret data on natural hazards to forecast future catastrophic events and inform the development of technologies to mitigate their effects). Our curriculum design uses an "embedded phenomena" framework* in which scientific phenomena are scaled to classroom size and become shared objects of collaborative inquiry.

Over the course of six lessons, students have to decide whether an event can take place, based on their weather predictions. Their classroom is an imagined geographic region approximately 250 x 250 miles. Students take tablet-based mobile weather stations (Figure 1) to different "towns" distributed around the classroom to record local ground conditions (e.g., rainfall, temperature, wind speed, wind direction, and moisture content). The data is based on historical records of actual measured weather conditions, collected by Argonne National Laboratory and aggregated in large datasets.

The stage is set for students to act as a local planner who must decide whether an outdoor event (e.g., a popular fun run or a traditional Alaskan blanket toss) can occur as planned. Using the weather station dashboard, the teacher initiates a virtual storm and students experience the weather event passing through their classroom (Figure 2). In the first two lessons, students capture temperature, precipitation, and moisture data over a series of time stamps and record it for the gridded region of their classroom. The teacher then pauses the simulated event, while students try to predict what the weather will be four hours later. After the teacher restarts the simulation, students can check the accuracy of their forecast.

Working in teams, students then transcribe the numerical readings from their weather stations onto gridded poster sheets representing successive points in time (Figure 3) to produce an aggregated history of the simulated phenomenon. Using colored sticky notes to represent temperature ranges, students create a more abstract representation that allows them to see emerging patterns (Figure 4). They estimate the values of "missing data" in areas that do not have weather stations using multiple interpolation methods (linear, nearest neighbor, and weighted average interpolation). The time series of maps produced in this way creates a visual storyline that allows students to extrapolate patterns and construct simple predictions of future weather conditions.

Classroom activities involve students in a broad range of activities—data aggregation and abstraction, pattern recognition, interpolation, and extrapolation—that are at the core of computational thinking and data analysis. Acting as an atmospheric scientist—collecting weather data from weather stations over a large area over time and organizing it into useful maps to predict weather—is an authentic and powerful way to immerse students in science.



Time: 11:46 AM

Temperature: 63°F / 17.2°C

Precipitation: None

Air Moisture: 0

Figure 1. Student group weather station display for grid E6.

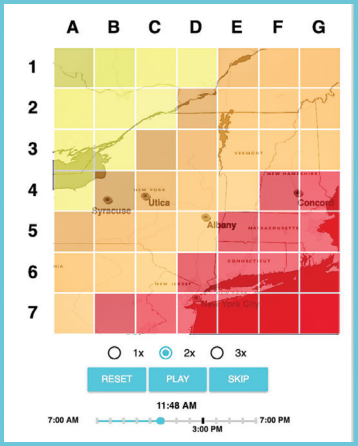


Figure 2. Teacher weather station dashboard for New England (with a comparable one for Alaskan students) showing the larger map of the region.

In subsequent lessons students continue using computational thinking skills such as interpolation and extrapolation to determine where it rains. Students revisit the weather maps they constructed earlier and add precipitation and air moisture data for additional time stamps. Next, students are introduced to a NetLogo model that allows them to test rules with the dataset they have been exploring. For example, they program a condition, like wind speed or air moisture, and see the resulting effects on precipitation. Students then investigate the role of wind in determining the weather by exploring the patterns of air movement within and between air masses. Using a hands-on "wind table," they study where the air comes from and how fronts move (Figure 5). In the final lesson students revisit the original question: Will the weather forecast force them to cancel the event?

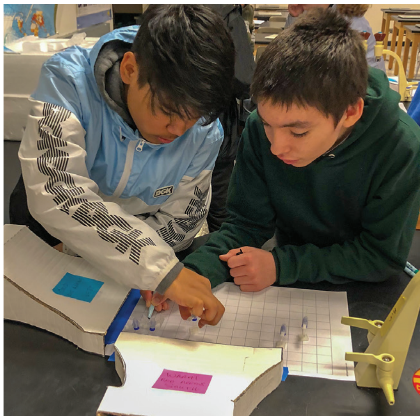
Research

Our research focuses on how enacted experiences, including classroom embedded phenomena, experimentation with real-world phenomena, exploration via computer modeling and simulation, and the use of authentic data representations, lead to understanding science, mathematics, and computational thinking content, and which learning environment designs foster and scaffold these experiences effectively.

We have piloted the Precipitating Change curriculum in three classrooms in Massachusetts and one in the North Slope of Alaska (near one of Argonne National Laboratory's three atmospheric research sites). Next year, we'll extend investigations to additional classrooms in two Native Alaskan villages to explore curricular changes that ensure maximum generalization and usability across classrooms through additional scaffolding and Universal Design for Learning affordances for English Language Learners. Our goal is to bring more weather talk informed by computational thinking skills and practices to more places—because everyone wants to know the answer to "What's the forecast?"

Figure 3. Students use computational skills to determine where it will rain.

Figure 4. The whole class records data and patterns from different time stamps in the weather stations.



Figures 5. Students use a wind tunnel to investigate wind direction.

LINKS

Precipitating Change
https://concord.org/precipitating-change

---

*Moher, T. (2006). Embedded phenomena: Supporting science learning with classroom-sized distributed simulations. Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI 2006) (April 2006, Montreal, Canada), pp. 691-700.

Under the Hood:

What Do We Do When There's Too Much Data to Look At?

By Paul Horwitz

Paul Horwitz
(phorwitz@concord.org)
is a senior scientist.

Many Concord Consortium curricular activities are delivered online, which means we can log student actions. This presents an opportunity and a problem. The opportunity is obvious: by analyzing student actions as they try to achieve a goal, we can infer their state of knowledge and use that information in contextualized real-time help or in summary reports. The problem? Logged event data tends to be rather voluminous.

Our Measuring Collaboration in Complex Computerized Performance Assessments project with ETS engaged postsecondary students from over 40 campuses and generated over a gigabyte—1.2 million rows—of log data. That's too much for a human but too little for machine learning algorithms, like those made popular by the Watson program that excels at Jeopardy. To bridge the gap we are developing software that enables researchers to sort and filter data before "drilling down" to interpret the actions of a particular student or team of students.

```
function findFilteredLevels() { //Returns an array of all the levels remaining after complete filtering
  var filteredLevels = [];
  for (var i = 0; i < attemptedLevels.length; i++) {
    myLevel = attemptedLevels[i];
    if ((RChatFilter(myLevel))) {
      if ((RCalcFilter(myLevel))) {
        if ((VChatFilter(myLevel))) {
          if ((outcomeFilter(myLevel))) {
            if ((levelFilter(myLevel))) {
              filteredLevels.push(myLevel);
            }
          }
        }
      }
    }
  }
  return filteredLevels;
}
```

Figure 1. Example of a function that computes the set of levels that correspond to the checked boxes.

In this project's activities, teams of three students work on separate but linked computers to solve a problem on a shared virtual electrical circuit, with four levels of increasing difficulty. (See "What Happens When Students Try to Work Collaboratively?" in the Spring 2018 *@Concord*.) A total of 139 teams attempted at least one level, with varying success. Each team generated a log file that recorded the actions of all the team members, including messages (students communicated only through a chat window), measurements, calculations, and alterations of the circuit itself.

The goal for each student on a team was to change the resistance value of their resistor to yield a specified goal voltage value known only to that student. Since their resistor was part of the team's virtual circuit, changes in any one resistor affected the voltage across all the resistors. Thus the team members' goals could be achieved only if they collaborated. For example, they could communicate with one another via chat and share their goal voltages if they chose to. Armed with all the goal voltages, it is possible for any student to calculate the three resistance values that would put the circuit into the desired goal state.

So, how well do students collaborate? Did teams communicate their goal voltages? If so, did they calculate and communicate everyone's goal resistance values? How do their actions differ across levels and correlate with the team's success?

We created a web-based interface in JavaScript that enables us to examine the log data and answer questions of this kind (Figure 1). The interface is, in effect, a simple but powerful filter of the original JSON log files. A researcher can select a level of difficulty (Levels A-D), focus only on teams attempting that level, filter by success or failure, and analyze the actions of successful or unsuccessful teams.

At Level C, for example, two teams succeeded *without ever chatting any of the goal voltages*. Since these teams could not have calculated their goal resistances, one wonders how they succeeded.

Thanks to easy filtering, we can do a bit more sleuthing into the data. One of these teams chatted just four times, all off topic. They did, however, collectively perform 36 resistor changes! Examining those changes clearly shows that the team members simply pursued their own goals, continually making slight adjustments to their own resistance value so as to keep their voltage measurement near their goal. This process gradually converged on the desired state and the team eventually succeeded.

We're currently programming the software to search for *sequences* of actions that will help us detect such strategies with some confidence. By combining software with evidence from our own eyes, we hope to illuminate the complex interactions that underlie successful (and unsuccessful) collaboration.

Innovator Interview:
Helen Quinn

Professor Emerita of Particle Physics and Astrophysics, SLAC National Accelerator Laboratory, and Chair, *A Framework for K-12 Science Education*, became chair of the Board of the Concord Consortium in January 2019.

Helen's interest in science began at the dinner table in her native Australia. Her engineer father would ask questions and expect Helen and her three brothers to argue about them. When she entered the University of Melbourne, she was a cadet meteorologist at the weather bureau and knew she would pursue science as a career. But when she was 18, her family decided to move to the U.S.

With two years of coursework from the University of Melbourne complete, Helen headed to Stanford, where she was admitted with three years of credit, counting her last high school year as well. Assistant Professor Jerry Pine encouraged her to audit courses and figure out for herself where she belonged. "Because of him, physics was the easiest major to complete in a year," Helen laughs. She stayed on, planning to complete a master's degree and become a physics teacher. But her plan was spoiled. "Physics was too interesting," Helen insists. Instead, she earned a Ph.D. in 1967, becoming one of very few female physicists in the world at the time.

For the next five decades, Helen pursued some of the biggest—and tiniest—questions in particle physics at Harvard and the Stanford Linear Accelerator Center (SLAC). She describes particle physics as "the most reductionist of sciences. We look at the very smallest things and the interactions between those that form everything we see." With Howard Georgi and Steven Weinberg, she demonstrated how the three types of particle interactions (strong, electromagnetic, and weak) become very similar in extremely high-energy processes. They hypothesized that when the universe was very young and hot—shortly after the Big Bang—these forces might have been unified into a single force, which then "broke symmetry" as the universe cooled.

Particle physicists know that for every matter particle there is a corresponding antimatter particle, with opposite charges. They also know that the laws of physics for antimatter are very similar to those for matter, except for a small difference that shows up in weak but not in strong interactions, which is a puzzle. Working with Robert Peccei she focused on how to modify the theory of these interactions, so that the strong interactions were protected from the symmetry breaking. That modification to the theory also predicts the existence of a new type of particle, dubbed the "axion." This particle, which has yet to be observed, is a candidate for comprising the so-called "dark matter" known to permeate the universe. "That's the wonderful thing," Helen muses, "We weren't thinking about dark matter. We didn't notice that we predicted that particle! Other people noticed that." The search for the axion continues to this day.

Helen's work spans both science and science education. When the Carnegie Corporation asked the National Academy of Sciences to develop *A Framework for K-12 Science Education*—the precursor to the Next Generation Science Standards—Helen was asked to direct the effort. She says, "I know what it means to do science, and I had been learning about science education. It was the right time for me to retire and take that on full time." She has been committed to the Framework's three-dimensional vision—linking disciplinary core ideas, science and engineering practices, and crosscutting concepts—ever since.

"The Concord Consortium fits that vision nicely," she says, supporting science education with an emphasis on students doing science like scientists, building their own models, and developing their own explanations of phenomena.

To read an extended interview and watch an interview with Helen, visit https://concord.org/helen-quinn

"We weren't thinking about dark matter. We didn't notice that we predicted that particle!"

The Concord Consortium
25 Love Lane, Concord, MA 01742

The Concord Consortium is spearheading the field of data science education. The following initiatives are preparing learners with the skills of data analysis so they are ready for future data science occupations.

Robert F. Tinker Fellow: Amy Hammett

Our first Tinker Fellow recipient, Amy Hammett, joins our Emeryville office this summer to work on ready-to-use, place-based instructional materials for teachers and students to develop data science skills using accessible tools. Amy currently collaborates with the National Science Foundation's Established Program to Stimulate Competitive Research (EPSCoR) on place-based problems. She describes their primary data as "gold for educators and students because it allows us entry into the adventurous world of real science—discovering that which is not yet known!"

She has also created exemplars for Achieve's Task Annotation Project in Science and piloted a unit under development for the Next Generation Science Exemplar team. She says, "Data science education can extend that work by having students and teachers use technological tools to uncover that which is unknown and hidden in big data, to computationally model those phenomena or systems, and to use the resulting model's predictive power to inform the design of solutions to complex, real-world problems." Amy is beginning a doctorate at Kansas State University in Curriculum and Instruction with an emphasis in Data Science Education in fall 2019.

Writing Data Stories

We're delighted to partner with the University of California Berkeley School of Education on a new grant from the National Science Foundation. "Writing Data Stories: Integrating Computational Data Investigations into the Middle School Science Classroom" integrates computational data analysis into the middle school science curriculum. Using our Common Online Data Analysis Platform (CODAP), students analyze public scientific datasets. Units designed with Dual Language Learners (DLL) in mind help students share their investigations through writing that blends familiar and academic modes of expression. Participants include 20 teachers and approximately 2,500 students from predominantly high-needs schools in the San Francisco Bay Area.

Project research asks: How do students learn, over time, to use computational tools to structure, calculate, filter, and transform data for scientific inquiry? What patterns of engagement in scientific practices are supported by the integration of computational data analysis and visualizations into the science curriculum? What new literacy practices support DLL and learners with limited access to technology in constructing oral and written arguments and explanations using data and visualizations as evidence?

Designing 2030: Thinking and Doing with Data

In January 2019, we hosted Designing 2030: Thinking & Doing with Data at the Gordon and Betty Moore Foundation to dive into questions around data and data fluency. Experts in data science education, data literacy, and citizen science from the Concord Consortium, BSCS Science Learning, the Gulf of Maine Research Institute, TERC, National Geographic Education, Nexmap, iNaturalist, University of California Berkeley, University of California Davis, and others envisioned the data-rich world of the future with the goal of designing learning experiences where students think, interact, and take action with data.

Concord Consortium President Chad Dorsey initiated the call for a "messy data" coalition and argued on behalf of messy data as a pedagogical context for developing data fluency and our future reality. Shannon Dosenmagen from Public Lab described how the BP oil spill of 2010 prompted her to organize communities to participate in environmental monitoring and activism. Lissa Soep from YR Media illustrated social media contexts for youth learning and empowerment in data-driven storytelling.

The Designing 2030 initiative is researching ways to support data fluency and designing tools and applications to support open data exploration, platform interoperability, and educational technologies.

Editor: **Chad Dorsey** | Managing Editor: **Cynthia McIntyre** | Design: **Jan Streitburger** | **concord.org**
The Concord Consortium | **Concord, MA** | **Emeryville, CA** | **978-405-3200** | **fax: 978-405-2076**
@Concord is published two times a year by The Concord Consortium, a nonprofit research and development organization dedicated to transforming STEM education through technology. This material is based upon work supported by the Gordon and Betty Moore Foundation, and the National Science Foundation under several grants (DRL-1620874, DRL-1742083, DRL-1640054, DRL-1418019, DRL-164008, DUE-1535224, and DRL-1900606).