@CONCORD

vol.23 • no.2 • Fall 2019

The Concord Consortium
CELEBRATING 25 YEARS
concord.org

Perspective:
The History and Future of Data Fluency

By Chad Dorsey

The Concord Consortium marks its 25th anniversary this year. That's an admirable length by any measure. In technology innovation years, it's practically eons. At our founding, in August 1994, the World Wide Web contained only a few thousand sites and the concept of ubiquitous powerful computers was barely more than a thought experiment. Although change is the only true constant in an organization founded on innovation, one of the most consistent themes running through our quarter century history is helping learners become fluent with data.

Decades before our founding, data was already beginning to play a central role in our work and vision. In the late 1970s, Bob Tinker adapted an early computer to collect and graph experimental data produced by a tiny temperature sensor. By demonstrating that physics students could do in minutes what had once taken them hours, and could see their results in real time as well, Bob inspired teachers across the country and launched a revolution in thinking about the role of data in STEM learning.

Today, the data revolution is fully upon us, engulfing industry and society alike. However, education is a very different story—the K-12 learner experience remains practically devoid of data. This poses a grand challenge for us as a society. Today's fourth grader is tomorrow's data scientist, worker, and voter. What are we doing to ensure that she can succeed and thrive? We're committed to answering that question, and aim to bring data to the fore across topics, grades, and settings.

Setting the stage

While it's been brewing for a while, we're now indisputably entering the Data Age. Data has, of course, been all around us for decades (even centuries), but the degree to which it defines our current world is wholly unprecedented. In fact, we've become so accustomed to the ubiquitous nature of data in our lives, it's easy to forget that the term "data science" was coined less than two decades ago and the practice itself has still barely been formalized. Standing on the brink of such changes demands recalibration across all sectors. Rethinking education is arguably the most urgent need of all.

There is precedent for such a tectonic shift, however. We stood at a similar inflection point with the rise of the personal computer. Over mere decades, computers moved from far-off novelty to fundamental business tool to everyday home appliance. As they did, it became clear that they would transform all aspects of modern life. This new age demanded new thinking, and a 1999 National Research Council report advocated for new paradigms: "Fluency with information technology … goes beyond traditional notions of computer literacy," they noted.*

While literacy "might call for a minimal level of familiarity with technological tools," they argued, a new age called for something deeper—learners now needed fluency with technology. Fluency with information technology represented "a deeper, more essential understanding and mastery … than does computer literacy as traditionally defined." The report suggested that success required a change in definition that could properly signal—and catalyze—this essential change in mindset.

Over the past decades, data has followed nearly the same path, moving from a novelty to (in some cases, quite literally) a home appliance. Like computers, data is poised to transform everything we do. Not to acknowledge the necessity of an equivalent shift in our relationship to and understanding of data would be reckless. Just as the NRC's call for IT fluency education was prophetic, it is time for an equally crucial change in the way we think about data.

So how do we proceed? What shifts in our view of education does this turning point require? In the same report, the NRC laid out some aspects of IT fluency. Individuals who were fluent with IT, they noted, would understand technology well enough to be able to apply it productively both in their work and everyday lives, "recognize when it would assist or impede the achievement of a goal," and be able to continually adapt to its

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

Learners must view data as a medium they can filter, transform, join, and summarize, moving and navigating within it as an artist does with paints or a poet with words.

changes and advancements. Substitute "data" for "technology" in that thinking, and the implication is clear—today's learners need precisely the same attitude and ability with data.

The notion of fluency is a valuable distinction. Most commonly played out in the context of language acquisition and reading, it connotes a sense of flowing grace and mastery. Timothy Shanahan described fluent readers as those who "can read like [they] speak." Gaining fluency also affords benefits—Kylene Beers describes how fluent readers "move easily from word to word, spending their cognitive energy on constructing meaning." In fact, in the realm of oral reading, fluency is among the best predictors of overall competence.

Changing our expectations

We can draw similar parallels with the world of data understanding. In other domains, literacy connotes only a basic level of comprehension or a simplified ability to read, translate, or decode. Arguably, that's just where we've been stuck for decades with data in education. At the most basic level, learners see data as something to be read—values to be looked up, like player names on a roster or numbers in a telephone directory. Cliff Konold and his colleagues have noted that students new to data analysis see this task as the purpose of graphs.

And why shouldn't they? It's what we have valued in education. While educators have been hard at work making sure students draw properly numbered axes and remember graph titles, creators of standardized tests have reinforced this basic sense of literacy. In an analysis of 274 items from state tests, Cliff Konold and Khalimahtul Khalil found that 78% demanded nothing more of learners than encoding or decoding graphs or tables to identify connected pairs of values.

This approach to data is not enough. We have been underserving learners for decades, depriving them of the ability to truly comprehend data's fundamental nature. We have inhibited them from seeing the world through the powerful lens of aggregated distributions, each with its own individual shape, center, and spread. We have protected them from grappling with the nature of measurement, structure, and complexity. But in a world of big data, continuing in this mode is unconscionable. Moving toward a more nuanced view of data understanding represents an acknowledgment that the world itself has changed. Data can no longer be simply looked at—it must be explored. Learners must view data as a medium they can filter, transform, join, and summarize, moving and navigating within it as an artist does with paints or a poet with words. The world of so-called Big Data, which is already exploding many of our existing notions of how to understand and work with data, demands such a fundamental shift.

The NRC recognized an analogous need on the eve of our last tectonic change. Information technology, they wrote, "is a medium that permits the expression of a vast array of information, ideas, concepts, and messages." To be fluent with technology requires "effectively exploiting that expressive power." We must view data in precisely the same way, preparing today's learners to be fluent in the medium that will shape our—and their—futures. Properly prepared, they will stand ready and eager to embrace data as the fundamental building block underlying the solutions to our modern challenges. The Concord Consortium has been paving the way for this revolution since our founding, and we invite you to join us.

* This article references several research reports and papers. Find links to all of them in the online version of this article.

Engaging in Computational Thinking

Through System Modeling

By Dan Damelin, Lynn Stephens, and Namsoo Shin

Dan Damelin
(ddamelin@concord.org)
is a senior scientist.

Lynn Stephens
(lstephens@concord.org)
is a research scientist.

Namsoo Shin
(namsoo@msu.edu) is an
associate research professor
at Michigan State University.

What is the effect of reintroducing wolves to Michigan's Isle Royale National Park? How is CO_2 affecting our oceans and the organisms that live there? How can something that can't be seen crush a 67,000 lb. oil tanker made of half-inch steel? Solving such questions requires thinking about the interrelated factors in a system: predators, prey, and various parts of a park ecosystem, for example, or carbon dioxide, acidity of the water, and shellfish health, and so on.

Most critical issues facing us today can be modeled as a complex system of interrelated components, involving chains of relationships and feedback between parts of the system. A common approach for understanding and solving problems such as these involves using a computer to simulate a model of the system. Developing and using system models requires computational thinking skills not only by the software engineers writing the code, but also by the entire team working to understand the system. A computational thinking perspective is necessary for everyone to contribute to decomposing the problem such that it can be modeled, tested, debugged, and used to understand the system under study. Indeed, the Next Generation Science Standards (NGSS) emphasize the importance of computational thinking and modeling using the lens of systems and system modeling.

Scaffolding Computational Thinking Through Multilevel System Modeling is a collaborative project with Michigan State University and the Concord Consortium funded by the National Science Foundation to explore how engagement in system modeling combines both systems thinking and computational thinking. Our goal is to investigate how students' scientific explanations are informed by the computational thinking they use while developing system models, and how engagement in constructing system models may develop students' computational thinking skills.

Contextualized framework for computational thinking

To guide our research, curriculum development, and teacher supports, we have developed a contextualized framework to illustrate how aspects of systems thinking (ST) and computational thinking (CT) overlap in the context of system modeling (Figure 1). In the diagram, systems thinking is presented on the left in yellow, computational thinking on the right in red, and the overlap contains the system modeling cycle in orange.

Within system modeling, the set of green boxes describes the phases of system modeling; the arrows represent the cyclic nature of engaging in the modeling process. Each phase marries aspects of both ST and CT. For example, to *define the boundaries of the system* involves *defining a system* from ST and *decomposing problems* and *representing data through abstractions* from CT. While designing and constructing a system model, students can compare the model output to some known behavior of the system under study. In this way students apply *modeling both conceptually and computationally* from ST and *testing and debugging* from CT. Such integrations occur throughout the framework. We believe that the interplay of systems thinking and computational thinking during the process of system modeling can promote growth across all three areas.

Multilevel system modeling

Engagement in system modeling has been historically difficult for students. Two obstacles have hampered this approach in K-12 STEM education: 1) students must know how to code or write equations to define relationships in the model and 2) creating a computable system dynamics model requires students to draw upon elements of computational thinking and systems thinking they are not typically exposed to, including an understanding of the nature of feedback in complex systems.

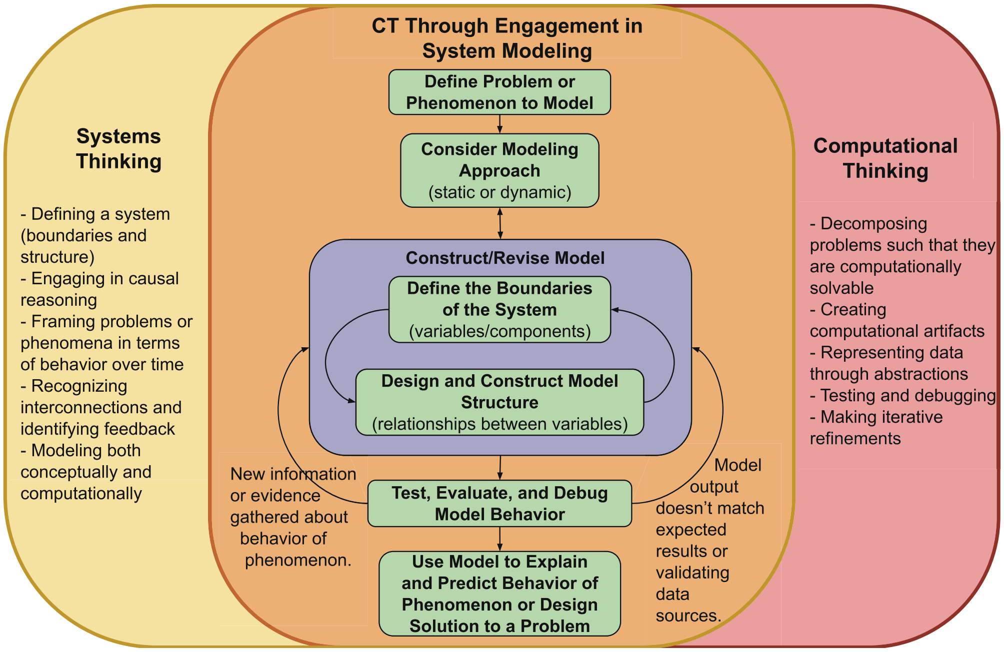


Figure 1. A theoretical framework of system modeling that combines aspects of systems thinking (left) and computational thinking (right). The overlap in this diagram (center) contains the system modeling cycle. This framework was developed by the project teams at Michigan State University and the Concord Consortium.

To overcome the first obstacle, we have been developing a system modeling tool called SageModeler, designed to provide an onramp to help students as young as middle school age design, create, and use system models. A simple drag and drop interface allows students to quickly select variables and define relationships between them, without requiring numbers, formulas, or coding. Quantities are represented on a scale of "low" to "high." Students consider how a change in the value of variable A affects variable B. Using words, menu selections, and pictures of graphs, students define the functional relationships between variables, then run their system model to test ideas about how complex phenomena work.

To address the second obstacle, we are exploring ways to scaffold students in the development of system dynamic models by focusing on key aspects of CT and ST as they relate to the modeling task. This scaffolding takes place both in the curriculum and within the affordances of the modeling tool. SageModeler supports three levels of complexity from model diagrams to static equilibrium models to time-based, system dynamics models (Figure 2).

Students can start with variables and links between them to form a system **model diagram**. As they include variables, they must consider the boundary of the system. Are the variables the right scale and scope for the phenomenon being modeled? Are the components of the model conceptualized as variables that can be calculated rather than just objects in the system? How do variables affect other variables? Even a simple model diagram provides rich opportunities for students to think about the system and begin engaging in both CT and ST.

To make the diagram into a runnable model, the relationship links between the variables need to be defined not just in direction, but in some semi-quantitative way. For example, in a model of climate change students might indicate that an increase in CO_2 emissions from factories results in a proportional change in CO_2 in the atmosphere. We call this a **static equilibrium model** where the effects of independent variables are instantly carried through the model, resulting in a new equilibrium state. With this kind of model the output can be compared with validating data sources to debug the model behavior and elicit revisions to better match real-world systems.

In **system dynamic models**, time can be introduced by defining one or more variables as "collectors" (traditionally known as "stocks" in system modeling). Students can also include feedback into the system and observe the behavior of the system over some defined time period. Because these models involve iterative calculations and can result in non-intuitive complex system behavior, especially when feedback is involved, we believe that this type of modeling provides the most opportunities for engaging in various aspects of both ST and CT.

By moving from simpler to more complex modeling approaches, we hope to overcome the difficulties students have had with building runnable system dynamics models, to engage them in understanding complex phenomena, and to foster both computational and systems thinking skills and practices. Learning how to support this approach is at the heart of our research.

Research into computational thinking

The following questions guide our project research on student learning and teacher practice:

1) How are students' scientific explanations informed by the computational thinking they engage in during iterative development of system models?
2) In what ways can curricular materials and technological tools best scaffold the development of students' computational thinking and system modeling practices?
3) How can teachers scaffold the construction and simulation of computer models to more thoroughly engage students in computational thinking practices?

We are working with high school teachers in Massachusetts and Michigan to investigate these questions. We are collecting student modeling artifacts as well as their responses to embedded assessments within curriculum units, and supplementing these data sources with screencast videos, lab and classroom-oriented observations, exploratory instructional sessions with individual students, and interviews of both students and teachers.

Embedded assessments in online curricular materials are used to evaluate changes in students' knowledge of disciplinary core ideas related to a particular phenomenon and their ability to construct and interpret explanatory models. After each iteration in which students build, test, share, and revise their models, they reflect on the state of their model and why they made any changes, and describe how well their model currently works to explain the

(continued from p.5)

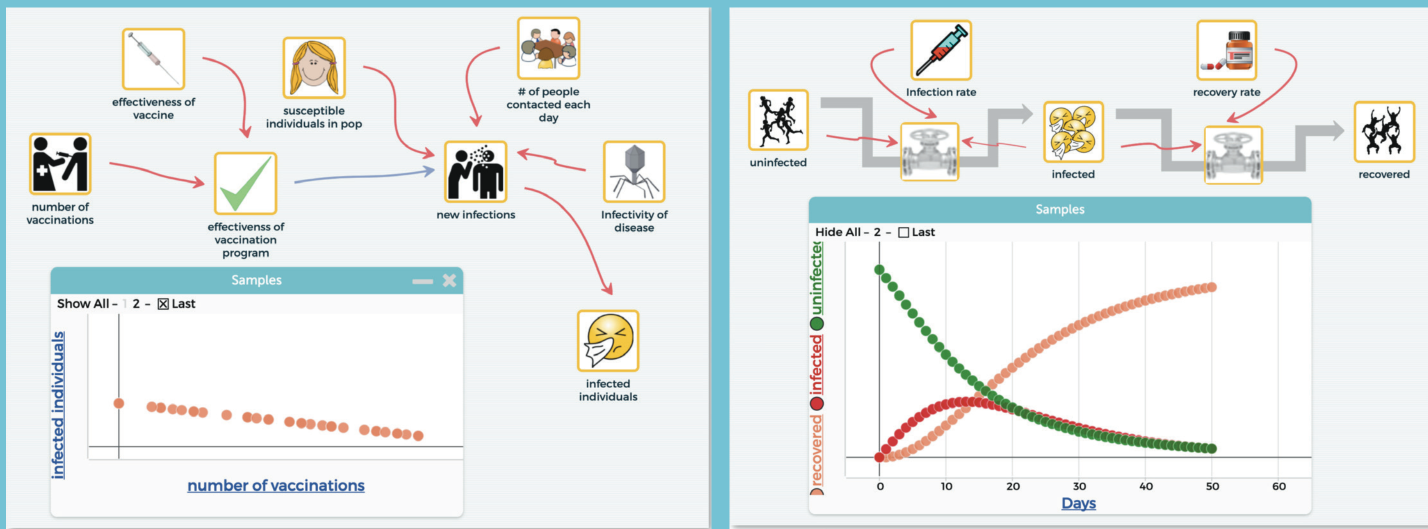


Figure 2. Two epidemic models. In the static equilibrium model (left) several factors affect the number of infected individuals. The graph shows that as the number of vaccinations increases, the number of infected individuals decreases. In the dynamic model (right), a collection of uninfected individuals becomes infected and then recovers. The graph shows how these three collections change over time.

phenomenon they are investigating. We log each iteration of the student model for post-analysis, including any tables and graphs of model output they created in SageModeler. Student models are analyzed for their ability to provide a causal account of the disciplinary phenomenon under study.

Screencasting software, which records student actions and audio from the computer microphone, serves to capture software usability issues, online curricular interactions and interpretations, and conversations among pairs of students while they are designing and testing their models. These screencasts allow us to explore how student modeling and computational thinking practices (especially testing, revising, and debugging) change over time. Interviews and longer exploratory instructional sessions probe student understandings of their models, how the models provide an explanation of the phenomenon, and the decisions students made when revising those models.

Classroom observation notes help us improve the SageModeler user interface, the curriculum design, and teacher support materials, including teacher guides and professional learning workshops. We also plan to explore supporting teachers in professional learning communities and will collect feedback about what kinds of supports they need and how well the materials scaffold teacher practices.

Curriculum units

We are currently developing curricula in biology, chemistry, and Earth science. All curricular units are NGSS aligned and designed using project-based learning (Krajcik & Blumenfeld, 2006*), with a driving question around a phenomenon of interest to students. First, students experience or are introduced to the phenomenon and develop an initial model about the driving question. Then they explore key aspects of the phenomenon and revisit their model to revise, share with peers, and engage in classwide discussion about the various approaches other students have taken. Students compare the model output to lab data they have collected or to publicly available datasets. Throughout the unit, they have multiple opportunities to iteratively test, evaluate, and debug their system model in order to explain and predict the behavior of the phenomenon or to design a solution to a problem.

To research how different levels of modeling may scaffold students' modeling practice and computational thinking skills, we are developing three types of units for each subject area: 1) a unit in which students develop a static model of the phenomenon, 2) a unit in which students develop a dynamic model, and 3) a unit in which students first model the phenomenon using a static modeling approach, then later transition that model to a dynamic version.

Our hypothesis is that moving from static to dynamic modeling may provide the stepping stones needed to make dynamic modeling accessible to more students. With a set of units that vary from using one type of modeling to using both static and dynamic, we hope to gain insights into what sequence of modeling experiences best supports growth in systems thinking, computational thinking, and system modeling. Developing these thinking and modeling skills is critical to the next generation's ability to participate in STEM fields and design solutions for present and future complex problems.

* Krajcik, J. S., & Blumenfeld, P. (2006). Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 317-334). Cambridge: Cambridge University Press.

LINKS

Multilevel Computational Modeling
concord.org/mcm

Bill Finzer (wfinzer@concord.org) is a senior scientist.

Randy Kochevar (rkochevar@edc.org) is director of the Oceans of Data Institute at the Education Development Center.

Monday's Lesson: Zoom In! Teaching Science with Data

By Bill Finzer and Randy Kochevar

In today's data-driven world nearly all scientific discovery involves delving into data. The Next Generation Science Standards (NGSS) include "analyzing and interpreting data" as one of the key practices and emphasize the need for students to engage firsthand with authentic datasets. A new set of six high school Earth and life science units are now available from the Zoom In! Teaching Science with Data project at EDC, developed in collaboration with the Concord Consortium. In each online unit students use the Common Online Data Analysis Platform (CODAP) to explore and analyze one or more real-world datasets. Each unit includes a comprehensive teacher guide.

Note that you can get off to a good start with this lesson on Monday, but you're unlikely to finish until Friday.

Population divergence: How are island lizards changing in the Skyros Archipelago?

Natural selection is one force of evolution that brings about the formation of species. Organisms living in different habitats experience different environmental conditions, which favor the selection of certain characteristics in one place and different characteristics in another. This can result in distinct populations within a species, or even a split into new and different species. Working with data collected in the Skyros Islands in Greece, students discover the influence of predation on lizards living on islands compared to those living on the mainland.

Get started by going to: https://app.zoominscience.edc.org

Sign up as a student with access code CrimsonOxford663

1. The Hook

Brainstorm answers to the question: What happens when populations are separated?

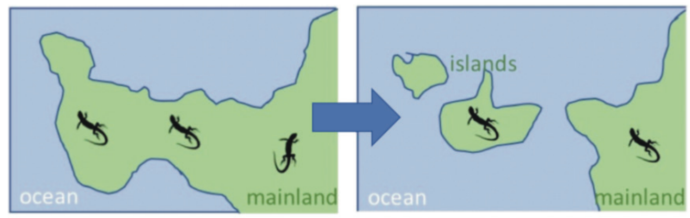
2. Background

Students learn how selective pressures influence natural selection's choices, how traits diverge during evolution, and how to measure evolutionary changes with mean and standard deviation. They also meet the researchers who collected the data and learn the methods they used to measure the lizards' traits.

3. Data Orientation

Use CODAP to explore data about lizards and to become familiar with the data structure and attributes. With 2 habitats, 13 locations, and 606 lizards, there's a lot to investigate! Change graph displays by selecting different attributes from the data table and dragging to the x and y axes. Select points or rows to see how the same data appear in different representations: map, graph, and table. Allow students plenty of time in this stage to "mess around" as they learn CODAP's features.

Over thousands of years, rising sea levels have caused lizard populations in Skyros, Greece, to become separated.



How—and why—might the island lizards have evolved differently than those on the mainland?

4. Investigation

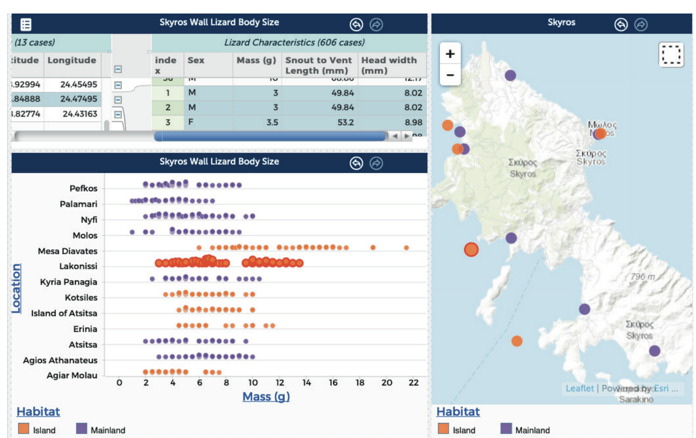
Working in three groups, students examine lizard body size, alertness, and protective coloration. They make hypotheses, construct graphs, analyze the data for mean and standard deviation, corroborate results, and present their findings.

5. Writing Task

Students turn the results of their investigations into claims, evidence, and reasoning to communicate their answer to the driving question: How are island lizards changing in the Skyros Archipelago?

The other Zoom In! units follow the same five-part structure, providing multiple rich opportunities to analyze data and answer engaging questions just as scientists do.

- Where will we find the next Earth?
- Where will the next big earthquake hit?
- What happened when wolves were reintroduced in Yellowstone?
- How will polymorphic animals survive a changing climate?
- How is climate really changing?



A graph of location versus mass, colored by habitat. Clicking a point in the map highlights the data in both graph and table.

LINKS

Zoom In! www.edc.org/zoom-teaching-science-data

CODAP codap.concord.org

Automating Detection of Engineering Design Practices in Energy3D: **Integrating Human and Machine Intelligence**

By Corey Schimpf

Corey Schimpf
(cschimpf@concord.org)
is a learning analytics scientist.

With the expanded adoption of project-based learning and the Next Generation Science Standards (NGSS), there is a growing emphasis on students engaging in authentic science and engineering practices that mirror professional practices. Incorporating both disciplinary content knowledge and strategies for using that content knowledge, practices reflect dynamic, flexible, and potentially highly transferable skills. Helping students engage in practices is important because they extend what students know to what students can do, enable them to wrestle with complex, open-ended challenges, and are associated with gains in both confidence and students' sense of self as a scientist or engineer.

In the case of engineering design, practices are often studied at a finer grain resolution than NGSS, though they can be hard both to define and to measure. Further, for many advanced practices, there isn't one canonical form they should take. As research on engineering designers has demonstrated, practices are often polymorphous and may be best characterized as falling on a spectrum from underdeveloped to highly developed.[1] Looking at how professionals apply practices can illuminate why they are so fluid. First, the kinds of open-ended challenges professionals face rarely have a single clear-cut trajectory from problem to solution. Second, professionals bring their own unique backgrounds, experiences, and preferred strategies to a given problem. Thus, coupling an open-ended challenge with these individual differences leads to a variety of ways in which practices are fruitfully enacted. This is also true for students.

As any educator who has attempted a project-based learning activity in their class knows, students simultaneously engage in a wealth of practices, at their own pace, throughout the activity. While teachers routinely keep track of their students, including which students are struggling and how the class is moving through an activity, observing all the practices in which students are engaging is daunting. This, in addition to the heterogeneous nature of many practices, can make it prohibitive to monitor and support all students on their progress in developing practices. New advances in technology and research are enhancing our ability to capture the diversity of students' practices and their idiosyncratic structure, helping both students and teachers of engineering design.

Advances in educational technology and research

Great progress has been made in developing logging systems for educational technologies as well as in techniques for extracting students' actions in a given platform. Open-ended simulation platforms that allow students to explore similar problems engineering professionals face offer one promising area for study. Critically, these platforms need to simulate a large part of the problem context and the types of actions professionals take in it in order to enable students to also engage in a wide variety of practices. In conjunction with a logging system, these platforms may be able to capture the diversity of students' practices in open-ended challenges. This raises another difficulty, however, in that logged actions in a wide interactive environment often result in messy data.

This is where advances in research come into play. While machine analysis may struggle over the messiness of the data, domain experts are able to analyze student log files, learn the forms their practices take in a particular context, and distinguish patterns they embody. Analysis from domain experts can then be programmed back into the machine analysis to automate this process. To see what this looks like, let's examine an example of different students' polymorphous practices from Energy3D, a computer-assisted design platform that enables students to design energy-efficient homes, solar panel arrays, and concentrated solar power systems.

1. Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education*, 101(4), 738–797.

2. Schimpf, C., & Xie, C. (2017). Characterizing Students' Micro-Iterations Strategies through Data-logged Design Actions. 124th ASEE Annual Conference & Exposition. Presented at the American Society for Engineering Education Annual Conference, Columbus, OH.

Engineering design with Energy3D

Our Solarize Your Home project tasks students with building a model of their home and designing a solar array for their rooftop in Energy3D. After asking their parents or guardians for information about the annual energy use for their home, students need to design a solar array to meet their energy need while staying within a certain budget. Energy3D offers a physics engine that enables estimation of the energy production of solar panels; it also includes tools for estimating the cost of associated materials. A central goal for this project is to give students an authentic challenge for learning about engineering design. Two critical engineering practices involve analysis and design iteration.

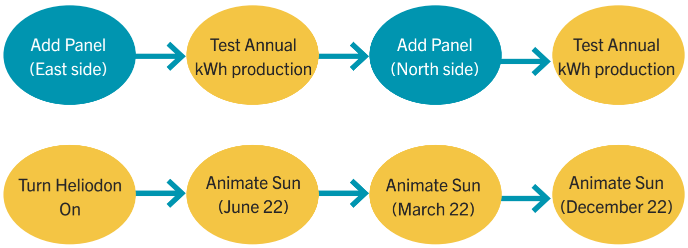


Figure 1. Two engineering design practices used in the Solarize Your Home project.

2A 2B 2C 2D

Figure 2. Screenshots of student work from Energy3D. Images A and B reflect the first practice (moving the solar panel from the eastern side of the roof to the northern), and C and D the second practice (only the heliodon on June 22 and December 22 are shown). Note: All images are looking south.

Figure 1 displays two simplified practices originally reported in Schimpf and Xie.[2] Each bubble represents an action or set of actions. These chains of actions form a complex practice encompassing both analysis and iteration. In the first example, the student places a solar panel on the rooftop of a virtual home (Figure 2A) and conducts an annual analysis to estimate the panel's energy production, and then moves the panel (Figure 2B) and conducts the analysis again (Figure 3).

In the second example, the student starts by turning on the heliodon, a simulated dome that shows the path of the sun for a given location. The student then "animates" the sun, which shows the path of the sun for a given day, beginning by showing the path in June (Figure 2C), and then repeating this for March and December (Figure 2D).

While at first glance these two examples—moving solar panels and using the heliodon—might seem like entirely different practices, our examination of when and how students were using these actions revealed in both cases that they were used early in their design process for the same goal: to gain a better understanding of the solar potential of their rooftop. In other words, they achieved the same ends through two different methods, one focused on a quantitative analysis of rooftop locations estimated through a single panel and the other using a qualitative visual analysis of how the sun faced the rooftop over different seasons. Across students, this single practice was polymorphous.

The pedagogical value of polymorphous practices

For design educators, capturing and displaying students' practices could assist in several pedagogical goals. First, a key lesson in design education is that there are many ways to approach a challenge and develop a solution. While teachers can discuss this in the abstract, showing how students engaged in different practices in their current project is a powerful way to demonstrate this principle about design and help students learn from each other. Second, another difficulty students face in learning design is the desire to find the "right" way. By comparing similar final designs, a teacher may also be able to show polymorphism in their practices, providing another demonstration that there may be multiple paths toward designing an optimal solution.

Although work remains on automating extraction of student practices identified by a domain expert, there are promising paths forward. One research strand ripe for investigation is the use of regular expressions in programming, which can search through strings of characters or actions and identify those that meet a range of requirements or patterns. We are also looking at machine learning approaches that are trained on patterns identified by domain experts and then classifying new chains of actions.

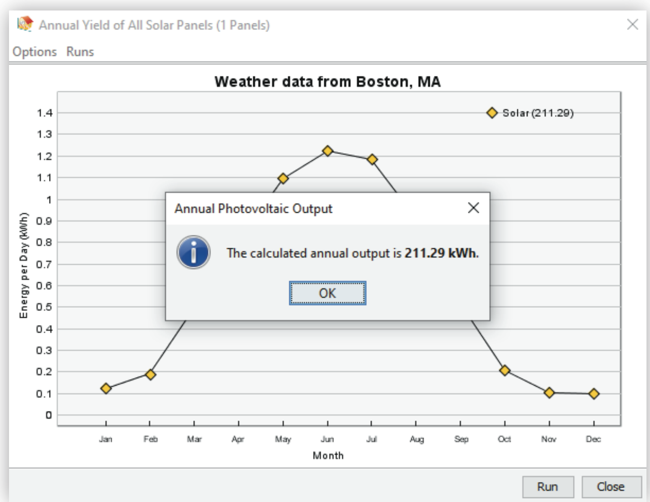


Figure 3. An example annual analysis of the energy production of solar panels.

LINKS

Energy3D
energy.concord.org/energy3d

Solarize Your Home
energy.concord.org/energy3d/projects.html

Young Children Explore the **Particle World with Apps**

By Nathan Kimball, George Forman, and Carolyn Staudt

Nathan Kimball
(nkimball@concord.org)
is a curriculum developer.

George Forman
(geforman@aol.com) co-directs
the Sensing Science project.

Carolyn Staudt
(cstaudt@concord.org)
directs the Sensing Science project.

Children learn by constructing knowledge. With each new experience, they test their naive beliefs (or in the research literature, their "theories in action") against the evidence. "What do I see/hear/feel? What do I know already? How does this relate to what I think I know?" They can then explicitly or implicitly affirm beliefs or reformulate theories. The Concord Consortium creates tools for children of all ages that provide firsthand evidence to test their developing theories and grow their knowledge about the world around them, including the hidden world of atoms and molecules that we can't see or touch.

It has long been assumed that the particulate nature of matter is too abstract for young children to understand. Traditionally, the particle-based world is introduced in upper elementary grades or later when children already hold well-formed but incorrect ideas that are consequently difficult to change. The Sensing Science through Modeling Matter project is developing and researching a technology-enriched curriculum to support learning about matter and its changes at the kindergarten level. How do kindergarteners understand and use particulate models to explain physical phenomena such as states of matter and phase changes? How should we design apps for kindergarteners to learn to model these physical phenomena?

Computer models provide virtual laboratories for experimenting with things that are too small or too large, take place over too small or large a time scale, or are too dangerous to do in the classroom. Models also allow students to change important variables and focus on the evidence for sense-making and theory building, while masking the intricacies behind complex systems that are not important for students to understand at this point. We have found that given the right tools, children as young as kindergarten age can discover patterns in models of particle motions and their interactions, and reason with their consequences. They gain a better scientific understanding of the world and open their thinking to cause and effect explanations beyond their immediate senses.

When contemplating how to design software for young students to help them develop theories of the particle world, we considered two approaches that exemplify different paths to children's learning. In one approach, students discover the patterns of particles that adhere to known physical laws; in the other, students construct the behavior of particles by setting rules for the way they interact and move.

The Particle Modeler

The Particle Modeler was designed for open-ended discovery (Figure 1). As an app for iPads and tablets, the Particle Modeler lets students "touch" virtual particles as well as see them. They drag particles with their fingers into a container, arrange them however they

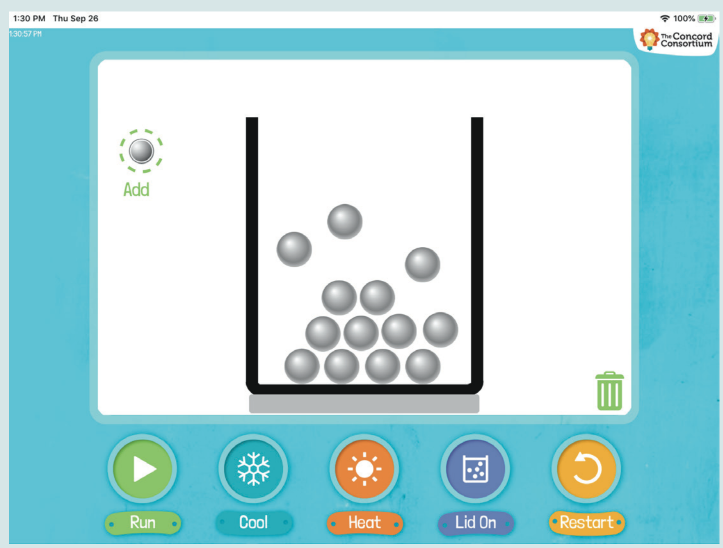


Figure 1. Particle Modeler. Students add particles and arrange them inside or outside the container; they can also cover the container with a lid. When the model is running, particles move according to the physical force between them and the force of gravity. Students heat or cool the system to observe particle behavior at a range of temperatures. Particles vibrate in place when they are in a regular structure as a solid, slide over each other when they are a liquid, and fly around as a gas.

want, and click Run to see the particles move under the influence of the forces between the particles and gravity. The particles bounce off the container and are attracted to each other if their distance and speed allows. Unlike balls, they never stop moving.

Students can increase or decrease the temperature and watch how the particles change behavior. For instance, if the particles are in an initial state of a solid (close together at a relatively low temperature), increasing the temperature causes the particles to speed up while vibrating in place. Increasing the temperature a little more causes the particles to flow around each other, representing melting from solid to liquid. A still larger temperature increase results in particles flying around each other as they evaporate to a gas. Lowering the temperature reverses the process. Students can create a solid by cooling, though the solid will not return to the original shape. Through this process, children discover important concepts about matter and states of matter: increasing temperature does not always change the state, particles in solids wiggle in place, particles in liquids flow over each other, and gas particles fly around.

The Thermonator

The Thermonator app was designed primarily to construct the rules of particle behavior using controls for four properties that affect the particles: speed, attraction, elasticity, and gravity (Figure 2). There is no explicit control for temperature. Students simulate temperature using the speed setting. They create arrangements of particles in different states of matter by finding combinations of all variables. To create a solid, for instance, they change the speed to low and attraction to high.

Additionally, in the initial model, two sets of particles are separated by a barrier. Students can change the variables for particles on either side of the barrier independently and predict what will happen when the barrier is removed (e.g., what happens to the speed of slow particles when bombarded by a group of fast particles?).

The Thermonator gives students control over the forces that cause temperature change and state change (e.g., fast and slow particles colliding), as well as the chance to choose settings that do not automatically yield the laws of particle motion. The ability to create examples counter to the laws of physics that do not work adds meaning to the settings that do. For example, students can set attraction to zero and see what happens—namely, that it is impossible to make a solid arrangement of particles. In other words, they learn that attraction is a key principle of physics, helping describe why particles must have some attraction to come together, but not fly away. Similarly, when students see what happens in zero gravity, they come to understand that gravity is required to make a liquid "sit" at the bottom of the container.

Similar goals, different approaches

Our goal with these apps is to help open a world of exploration and develop an explanation for the changing states of matter that children see around them. Both provide playgrounds for young children to experiment with cause and effect.

The Particle Modeler demonstrates the physically correct behavior of particles influenced by different temperatures and gravity. Children observe the combined properties of particle attraction and speed on particles that they can arrange to make different states of matter. The Thermonator, on the other hand, requires knowledge of the separate properties. Children must figure out how to combine speed, attraction, elasticity, and gravity to create specific states of matter. These variables give children the opportunity to reflect upon and repair a theory in action that does not work.

We are in the early stages of fully understanding how best to introduce particle motion to young children. Our hypothesis is that the two different approaches may complement each other. Integrating them may help students build a more complete understanding of the particulate nature of the unseen world.

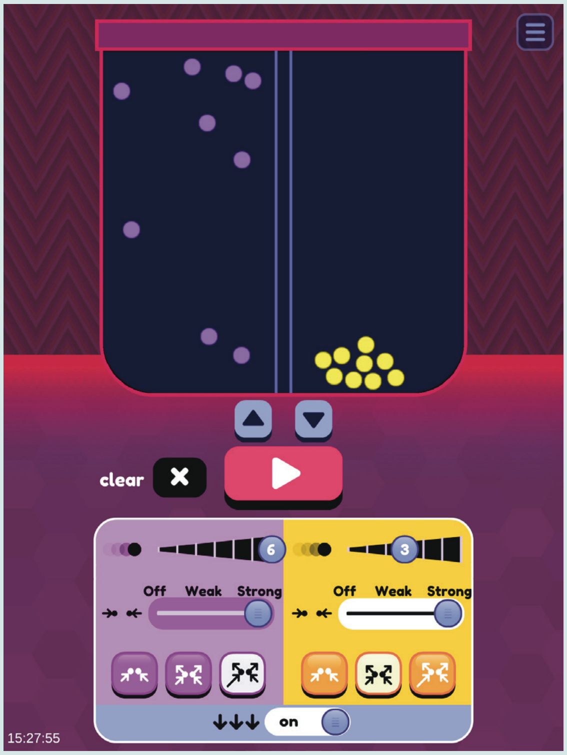


Figure 2. Thermonator. Students start with random arrangements of purple and yellow particles in the two compartments of a container. They set properties of the particles—particle speed, the level of attraction between particles, and the way they interact (elasticity) for each side of the container—and turn gravity on or off, then run the model to see how they behave. Students can remove the barrier between the compartments to observe the interaction between particles with different properties.

LINKS

Sensing Science
concord.org/sensing-science

Sensing Science iPad Apps (free download)
concord.org/sensing-science-apps

Particle Modeler
particlemodeler.concord.org

Thermonator
thermonator.concord.org

Investigating Smart Museum Exhibits

By Sherry Hsi

Sherry Hsi
(shsi@concord.org)
is Executive Vice President of
the Concord Consortium.

Students spend more waking hours outside of school than in school. It's no wonder that learning takes place not just in classrooms, but in different informal learning settings at home, around town, and in other community spaces. Technologies are also all around us. Our Learning Everywhere initiative aims to explore ways to bridge, extend, and connect school learning to other learning experiences across settings, using the best features of technology.

We are partnering with museums to understand how to transform exhibits into both learning amplifiers for visitors and data collectors for learning researchers. Ubiquitous computing technologies embedded in hands-on interactions and physical spaces offer opportunities for learning—and for learning about learning. A "smart" museum or exhibit can collect data about its visitors for institutional purposes and to benefit the users' own learning by engaging them in experimentation, dialogue, and reflection.

Using wireless networks, data analytic tools, and artificial intelligence, smart museums leverage the actions and movements of users that trigger sensors, switches, and touchscreen devices to track and gather user or customer insights. Digital data can be collected from visitors using cameras, barcodes, eye tracking, RFID, and mobile devices. These cyber-enabled technologies capture data about visitor location, body positions, game play, and exhibit preferences.

For example, wearables like tracking devices and personal mobile phones can monitor user location and gross body movement, while beacons, transmitters, and tags monitor a user's position and path within the museum. These technologies vary in their robustness and accuracy with respect to documenting visitor activity, as well as in their inconvenience, expense, and disruption to the learning experience. Less intrusive methods embed sensors and tracking into exhibit spaces to gather digital data in the background without interrupting the flow of visitor activity.

Sketch Town case study

With the Children's Creativity Museum in San Francisco, we are studying how technology can help facilitate and document the ways families contribute to their children's learning. We collected baseline information from an existing media exhibit called Sketch Town using monitoring techniques. Sketch Town uses art and technology to inspire family conversations about being part of vibrant urban communities.

As they enter the Sketch Town gallery space, families sit together at a table and draw on paper templates marked with a machine-readable code. They can color in an existing shape (e.g., a bus, building, or rocket), or make their own sketch. After completing a drawing, the user digitizes it on a nearby tabletop scanner. The drawing then appears on a large wall display along with other user-contributed, interactive images (Figure 1). For instance, if the image is a car, it moves along the roads in a large city landscape scene. Visitors can touch the wall to make sketched objects behave in different ways, such as making a house jump and play chimes.

To test different methods for capturing visitor interactions, we tracked how families used the exhibit over multiple sessions. (A sign was placed at the entrance to Sketch Town, using an implied consent approach to notify visitors that they were being photographed with an overhead camera. Visitors were not personally identifiable on the photographs.) We used both traditional human-led data gathering techniques (including observational ethograms, scan sampling, and surveys), as well as common technology-based monitoring strategies (Figure 2). For example, to look at raw usage data, we used interaction log files from the exhibit, along with a time-lapse digital camera mounted near the exhibit to take periodic snapshots. We also counted the number of paper sheets used by visitors in a given day, plus date and time stamps from the computer's digital scanner, to track how many images were created. Finally, we held brief interviews with parents and caregivers.

Results

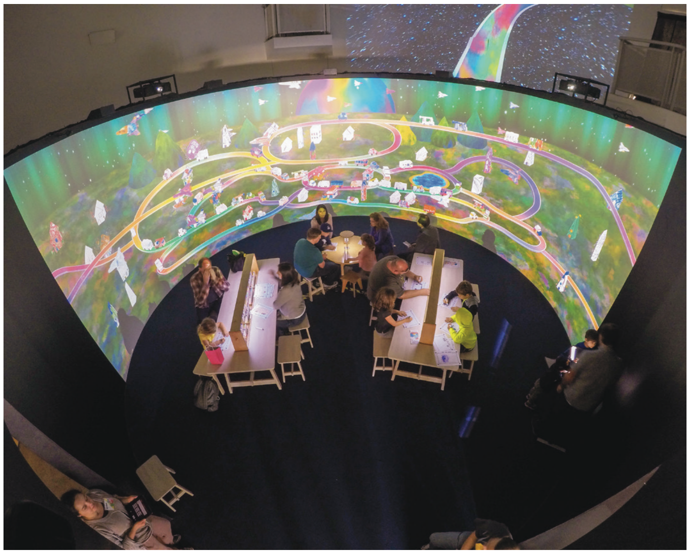
Sixty families offered to share their feedback with researchers. We asked parents about their family's experience using Sketch Town and what they thought their children were learning at the exhibit. Their responses ranged from learning about technology and "getting a sense of how scanning works and how physical objects become digital" to art appreciation. One father remarked

Figure 1. View of the Sketch Town exhibit with an interactive wall display. A second screen above the main display shows a moving view from a digital flying helicopter in the city scene.

that the exhibit was teaching his daughter "how to appreciate her art and her friend's art" as the work was posted to the gallery wall. Another family mentioned that Sketch Town was teaching their children the important science concept of "cause and effect" as they interacted with their digital wall drawings.

When asked if they wanted the museum to send the digital recording of their child's work, about half of the parent groups felt this could be a useful feature, allowing them to focus more on their child while at the museum. Parents suggested that the digital artifacts could be shared with other family members or used to prompt further reflection about the museum visit.

We also surveyed the feelings families had about being recorded by a "smart" exhibit. A majority (just over 60%) agreed to the general use of recording visitors to improve the experience. And almost 90% of the parents did not have privacy concerns about such museum research. Because of the deep trust that has been established over time between visitors and the Children's Creativity Museum, they were willing to provide data to help improve the exhibit learning experience.



Opportunities and challenges

In museums that serve young children and families, all program studios, theaters, and galleries are highly regarded as secure public spaces in which to learn and explore, safeguarded by museum staff and the institution's researchers. Strict design requirements ensure that the parent-child interactions as well as family learning spaces are preserved, maintained, and respected. Thus, methods for collecting smart museum data pose both a human-centered design opportunity and a serious challenge.

Our goal is to investigate what kinds of information can be inferred from digital data captured from users' interactions with an exhibit, as well as from their interactions with each other, that do not require the use of visitor-worn beacons or other wearables. (With technologies like card readers that trigger an exhibit response, visitors choose when they want to be recorded.) Less visible embedded technologies rely on strong trust between the public and the museum, and collect data using methods of implied consent.

In our exploratory study, the data gathered from Sketch Town gave us insights into the complex socio-technical issues of smart exhibit methods. Research from this study could inform other exhibit developers who are contemplating whether to incorporate user tracking data that assists informal educators, teachers, and visitors to better understand how to support users in real time or to enhance their later out-of-museum learning.

We are continuing to explore different ways a museum exhibit can enhance a visitor's experience while also helping to gather useful information for museums. We also want to improve upon a user data model developed from unobtrusive, yet transparent collection of data. If exhibit interactions are designed to encourage visitors to reflect on their own learning and parents to record their children's learning, digital tracking and documentation functions may become learning amplification tools.

Figure 2. A view of the Sketch Town exhibit captured from a time-lapse camera used to track visitors.

Under the Hood:
Sharing the Sky in an AR Planetarium

By Nathan Kimball and Chris Hart

Nathan Kimball
(nkimball@concord.org)
is a curriculum developer.

Chris Hart
(chart@concord.org)
is a senior software developer.

"Look over there, that's Orion. And there's Ursa Major." If you can you pick out the stars in the night sky and understand how they move, there's a good chance someone taught you by pointing with outstretched arm to the landmark constellations, marking the paths across the sky, and dividing the myriad points of light into recognizable patterns. Knowledge of the night sky tends to be passed on through an oral tradition combined with physical gestures.

Traditional ways of learning about the stars and motions of the sun, moon, and planets employ elements common to augmented reality: collaboration and embodiment. The CEASAR project (Connections of Earth and Sky Using Augmented Reality) is researching methods of collaborative problem-solving using augmented reality (AR). With AR, users see their surroundings superimposed with digital objects, making collaboration possible because learners can see and communicate with those around them. But there are few educational examples of AR. Our goal is to demonstrate the benefits of an immersive augmented reality platform for collaborative learning and problem-solving.

CEASAR is building on social, situated learning that incorporates dialogue, gesture, and 3D learning to teach about astronomy. We are developing a model of the sun, moon, and stars that mimics a real view of the sky surrounding the user, like a planetarium (Figure 1). Students can opt for multiple perspectives, including both the classic celestial sphere model (Figure 2), which resembles a "ball of stars" with the Earth at the center, and the familiar heliocentric solar system model (Figure 3).

The 3D holographic models are superimposed in physical space, like a classroom. With devices to view the models, students learn about the heavens using gestures and conversation to share observations. They are able to move around and change their gaze, and collaborate with others who may be viewing different models or looking at the sky from different vantage points.

The models run on Microsoft's HoloLens, a self-contained wearable holographic headset with a great degree of 3D immersion and the ability to capture the user's gestures. We will also support more common devices typical in classrooms, including tablets and phones. To do so, we're leveraging the cross-platform publishing features built into the Unity game engine to render the same star models on a web client, a native desktop application, and on both mobile devices and the HoloLens. We are currently able to render the brightest 9,000 stars (from a free database) in 3D, projected onto the surface of a sphere that can be viewed from inside or outside the orb. Using calculations for date and time, we are able to rotate this celestial sphere to any moment in the past or future.

We have also implemented networking using the multiplayer game server Colyseus running on Heroku in order to allow users on different devices to share their observations. Students can now highlight constellations to share with a friend—just as if they were pointing to the real night sky.

Figure 1. Planetarium view. Constellations appear in different colors. Stars can be selected and identified. Orion is in red; Gemini (to the East) is in blue.

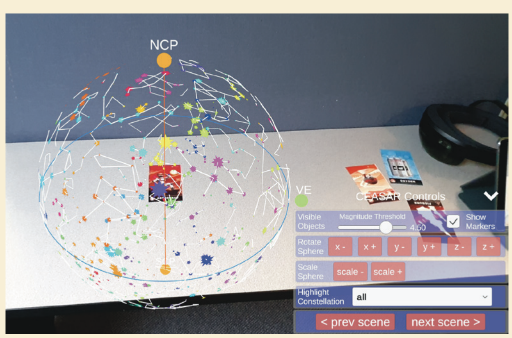


Figure 2. Celestial sphere. The sphere sits on a target that provides a common location for shared viewing on different devices. The number of visible stars is set by the Magnitude Threshold.

Figure 3. Sun, Earth, and moon mockup model. Note that the sun illuminates the moon and Earth. If the targets are moved, the illuminated part stays oriented to the sun.

Innovator Interview:
Ethan McElroy

emcelroy@concord.org

"One lesson about creativity came from a college art instructor who taught drawing 'as discovery, the act of finding.'"

As a teenager in the '90s, Ethan had access to the nascent World Wide Web through a local ISP and Netscape Navigator. His curiosity led him to learn HTML by copying web pages as a template for creating his own. An English and fine arts major at the University of New Hampshire, he tried formatting poetry on the Web. One early puzzle was figuring out how to right align text. "That's child's play," he observes, but at the time, without WYSIWYG editors or an obvious source for the answer, he had to work at it. That challenge—and his interest in solving it—would launch him into a career. Ethan has been the Concord Consortium's webmaster since 2010.

Ethan took his first job at a market research firm in Boston after college, part receptionist and part "web trainee," because of the learning opportunities it promised. When the webmaster assigned to teach him the tricks of the trade left, Ethan learned Perl, PHP, and JavaScript on his own and with the help of his computer-savvy boss. He was also a regular visitor to the "incredibly informative and fun, but sadly long defunct" tutorial website Webmonkey.

Ethan describes the early days of the Web as "fragmented, a sort of Wild West." At the time, he drew inspiration from sites like Superbad.com with its quirky experiments, and what seemed like a never-ending parade of new technical developments and tricks appearing all around the Web. Reading Jeffrey Zeldman's *Designing with Web Standards* and discovering the Web Standards Project and A List Apart mailing list helped him to learn "the craftsmanship of creating well-structured and semantically meaningful HTML."

According to Ethan, one of the most exciting changes over the history of Web development has been the ability to do things in the browser without plugins. "The evolution of JavaScript is pretty amazing—from simple things like making images change on mouseover to becoming more of a full-fledged development language." These days Ethan checks alistapart.com, awwwards.com, and Webdesigner News to keep up with the creative ways the Web is developing.

One important lesson he has learned about creativity came from a college art instructor who taught drawing "as discovery, the act of finding." For Ethan, a natural artist who had always been very careful with his drawings, tossing them out if they weren't perfect, the idea of leaving sketch lines as the history of his search for the "correct" line or shape was freeing.

Though he doesn't draw or paint a lot these days, Ethan still creates art in the digital realm. He has also picked up photography, in large part to document a progressive 19th century psychiatric hospital building design advocated by Philadelphia psychiatrist Thomas Story Kirkbride. Fascinated by the contrast between the rational and irrational represented by these buildings, Ethan has visited and documented most of the few remaining Kirkbride sites throughout the U.S.

He has also nurtured a longstanding love of music, writing and recording his own songs—even creating an original recording of the late Freddie Mercury! Taking voice clips from the lead Queen vocalist, Ethan broke them into words, syllables, and single vowels and consonants, arranged them into lyrics he had composed, then used pitch correction to form them into a unique melody. During the process, Mercury's words and voice sparked ideas for a new verse and an original bit of improvisational scat singing. Like searching for the correct shape in his artwork, Ethan has sketched in phonemes to find the music. He says, "It's all about discovery."

The Concord Consortium
25 Love Lane, Concord, MA 01742

Teacher Ambassador
Christine Fernandes

25 Teacher Ambassadors

We are proud to announce a new Teacher Ambassador program. To commemorate our 25th anniversary, we are recognizing 25 outstanding teachers who have included our digital inquiry resources into their kindergarten to high school STEM classrooms. We congratulate them on their innovation and creativity. Learn more: https://concord.org/blog/topic/teacher-ambassadors

Watershed Awareness and STEM Careers

Across the country, every minute of every day, water glasses are filled from a tap, laundry is washed, and baths are run. How does the water get there? Where does it go? Who helps to assure that our water is safe? As the need for clean water increases with a growing population, so does the need for increased participation in water careers. A new project funded by the National Science Foundation (NSF) is aimed at broadening the population of students who believe they have the ability and skills to pursue STEM careers with certification and associate degrees, as well as with bachelor's and higher degrees. The Watershed Awareness Using Technology and Environmental Research for Sustainability (WATERS) project is developing and researching a student-centered, universally accessible curriculum for teaching water concepts and water career awareness. The curriculum incorporates hands-on local data and geospatial analysis to explore geographic, social, political, and environmental concepts and problems related to watersheds. WATERS applies Universal Design for Learning principles to create a scalable approach to water learning that provides flexible information presentation and student responses, and offers appropriate supports and challenges.

Educating Designers for Generative Engineering (EDGE)

The University of Arkansas, Massachusetts Institute of Technology, the University of Illinois at Urbana-Champaign, and the Concord Consortium are collaborating on a new engineering design project funded by NSF. The goal of EDGE is to define, implement, and disseminate a new framework of design thinking based on the revolutionary technologies and methodologies of generative design driven by artificial intelligence. Design is being transformed by computation, and today's engineers must understand how computers "think" in order to harness the power of generative design effectively. The new framework will be infused with computational thinking that empowers future engineers to consider design from a computational perspective. Project research will be based on our free Energy3D integrated computer-aided design and engineering software. A set of online learning modules in mechanical, energy, and civil engineering will guide students to solve authentic design challenges using both traditional and generative methods. With data collected from over 2,000 students, researchers will investigate how students' design solutions improve and how their design thinking evolves as a result of transitioning from a traditional design method to a generative one.

Understanding Weather Extremes with Big Data

A new NSF-funded project aims to promote important scientific data practices and interest in big data science careers among middle school students in underserved New England rural areas. Understanding Weather Extremes with Big Data: Inspiring Rural Youth in Data Science is developing and researching four model curriculum units and an interactive experience with weather scientists. The two-week data investigation units provide students with hands-on opportunities to analyze and model large-scale weather data collected from Mt. Washington in New Hampshire (the highest mountain in the eastern U.S.), and data collected from students' local weather stations. Students will describe, explain, model, and predict extreme weather events in their local settings and at Mount Washington Observatory, which has recorded some of the most extreme weather conditions in the world. Students will use the Common Online Data Analysis Platform (CODAP) and SageModeler to visualize, model, and analyze large-scale data. They will interact with weather scientists through virtual chats to both deepen their understanding of their own data investigations and to gain insights into scientific careers that use big data.

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 William K. Bowes, Jr. Foundation and the National Science Foundation under several grants (DRL-1842035, DRL-1621289, DRL-1503196, DRL-1621299, IIS-1822796, DRL-1850051, DRL-1918847, and DUE-1918847).