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Perspective:
An Exercise in Humility

By Chad Dorsey

As the world gradually awakes from over a year of pandemic-induced suspended animation, I am grateful for something rare—a moment for reflection. What have we learned? What do we appreciate differently? While there are many lessons to be gained from looking back, the most important involve looking forward to consider how we can prepare the next generation for future challenges. We should ensure that the next generation gains from what we have learned. However, I believe the most important legacy we can leave lies in conveying a deep appreciation for all the things we *don't* know.

The early stages of the pandemic provide an intriguing perspective on how people think—together and individually. A recent episode of "The Ezra Klein Show" interviewed sociologist Zeynep Tufekci, who advocated for a number of important actions at the onset of the coronavirus pandemic. Her comment addressing the importance of exponential functions in the context of viruses stuck with me: "It's very hard for normal people to think about exponential growth, because it's not ordinarily part of our everyday experience."

This statement is deceptively profound, and resonates with me personally. My early experiences with the power of exponential growth remain vivid—I may have lived in the era of Star Wars and ICBMs, but exponentials kept me up at night, as I read predictions of global overpopulation and pondered math puzzles about rice grains multiplying on chessboards. Exponential functions are truly insidious, plodding along practically unnoticed for what seems like forever, then exploding—in a way that at first surprises, then shocks—in the blink of an eye.

The most compelling thing about exponential growth is that it makes starkly clear that the future is not always what we expect. This same lesson can be found in many places. In her timeless essay "Dancing with Systems," systems thinking giant Donella Meadows describes her journey coming to appreciate the depth and nuance of complex systems and learning that "self-organizing, nonlinear feedback systems are inherently unpredictable. They are not controllable. They are understandable only in the most general way." This means, she writes, that "the goal of foreseeing the future exactly and preparing for it perfectly is unrealizable." In the end, Meadows notes, "we can't surge forward with certainty into a world of no surprises, but we can expect surprises and learn from them. . . . We can't impose our will upon a system." While this may have the ring of an alarm bell, she writes from a place of hope, describing in poetic terms how humans can not only work within complex systems, but learn to "dance with them."

Unfortunately, this is not a lesson humankind is particularly good at learning. The journalist and chronicler of the natural world John McPhee outlined specific cases of this kind of human vanity in his iconic book *Control of Nature*. His vivid descriptions of human attempts to control rivers and volcanoes in order to craft predictable outcomes demonstrate how easily hubris must give way to humility in the face of nature's complex systems. When we face nature's unpredictability, whether in the form of unruly exponentials or complex systems, experience becomes a crucial guide.

Non-scientists are no less aware of this dynamic. Food writer and minimalist cooking proponent Mark Bittman describes the four stages of learning to become a truly good cook. By the fourth stage, cooks have repeated basic recipes and their variations so many times that "many options are in your head and at your fingertips." This, he argues, is how chefs ultimately learn—by drawing upon repeated experience. Cognitive scientists call this "case-based reasoning" and hold it up as a model of how experts approach the world. Intuition is an outcome of this same process; we reason and generalize from cases we have encountered in the past.

Although exponential functions and kitchen skills seem very different, they are both lessons in humility. Experience teaches us not only what we can do, but what we can't. If we're lucky, it also helps us gain the humility to apply the things we understand to situations we don't and to appreciate the limitations involved.

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I believe the most important legacy we can leave lies in conveying a deep appreciation for all the things we *don't* know.

Scientists regularly employ formal uncertainties as part of their process. Whether measuring the length of a molecular bond or predicting the probability of the next earthquake, scientists report not only a number but also a range representing their degree of certainty with the measurement. This does more than merely communicate results accurately. Uncertainties serve as guardrails, shielding us from straying too far into the unknowable.

It turns out that delineating the unknown is often valuable. Thomas Edison insisted that he had never failed, but merely "discovered ten thousand ways that don't work." Sociologist Damon Centola discovered that the common assumptions about the "viral" spread of behaviors were fundamentally flawed. Acknowledging these longstanding errors and thinking differently, he proposes, could lead to revolutionary advances in our ability to understand and foster uptake of all types of behaviors, from mask wearing to agricultural or medical processes and beyond.

As we emerge from our pandemic stupor, what does this all mean for how we help prepare the next generation? Here's my short list:

- Fear the exponential—learn about exponential functions both as a mathematical exercise and in real-world applications.
- Learn to dance with systems—embrace humility about the true complexity of complex systems.
- Acknowledge all that we usually don't know—recognize and take note of the built-in uncertainty the natural world harbors in all places and situations.
- Find value in that unknown—remember that markers of the unknown can be jumping-off points just as easily as they can be guardrails.
- Expect surprises—by remaining humble, we can acknowledge and welcome the unexpected.

But how do we help students *learn* these big ideas? Just as the master chef repeats and varies fundamental recipes over and over, the key lies in experience. If students are to identify the world's key principles, understand the dynamics of interdependence, and appreciate the importance and nuance of uncertainty, they need repeated, hands-on experiences. They need to push the boundaries as well as understand the guardrails.

Real-world experiments are essential for science learning. But many of the most critical ideas in our world defy direct interaction. How can learners interact with molecular bonding? Appreciate the complexity of a virus spreading worldwide? Watch the dynamic ramifications of tectonic plate shifts? Gaining experience with complex systems or intricate phenomena across scales of time and space is critical for appreciating the world we live in.

Fortunately, technology can enable this crucial inquiry, further vital exploration, and give learners agency—from models and simulations that reveal scientific phenomena to data visualization and system modeling tools that make it possible to find patterns. Students need repeated experiences and multiple opportunities to answer their own questions and identify the limits of knowledge and the uncertainties involved.

If we find the right combination of real-world and technology-enabled experiences, we can launch students on journeys of learning richer than ever before. Doing this provides the hope we can pass on to the next generation. If we equip students with a robust set of experiences, we prepare them to view the frontiers of knowledge as opportunities rather than limits. Students will have the confidence, and tools, to lean into a future of unknowns.

Integrating Technology and Science:

Preparing Students for the World They Live In

By Lisa Hardy

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As science educators our goal is to help students engage in and develop practices for understanding the natural world. But what about the built world, the human-made environment—the one that students spend much of their day-to-day lives in? We teach science for many reasons: to prepare students to develop thinking skills and understand the world around them, to engage as citizens in their communities, and to enter the workforce. We should teach about technology for the same reasons.

Our modern technological world is rapidly changing, and most people know little about the technological forces that are reshaping their work and home life. From a household smart thermostat to autonomous vehicles, from an Amazon Dash button to the "Internet of Behaviors," our world is sensed, interpreted, and algorithmically controlled by technologies we didn't create ourselves. Many technologies on the horizon (e.g., "deepfakes" and art generated by machine learning algorithms, gene editing with CRISPR, artificial general intelligence) will fundamentally change how we live and relate to one another. Yet school does little to prepare students to understand—let alone change—this increasingly technological world.

Moreover, nearly every future job is going to require unprecedented competence in working with technology. Workers will need a complex mix of creativity, knowledge, and specific competencies, such as interpreting data from sensor networks or training machine learning algorithms. Whether or not a student ultimately pursues a career in STEM, it is nonetheless empowering to be able to understand, adapt, and change the built world. And because science and technology are deeply entangled, science classrooms are an ideal place to look for opportunities for teaching with and about technology.

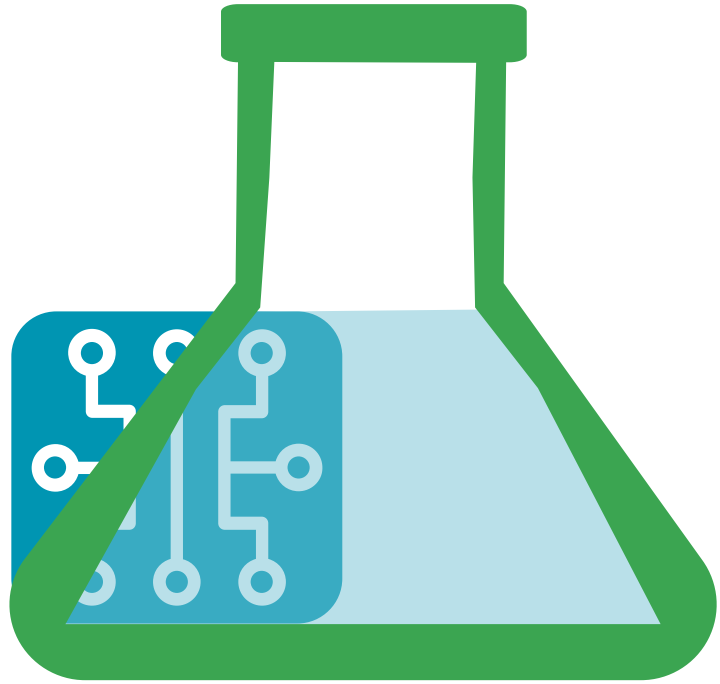
How do science and technology progress together?

Science education includes learning about how scientific knowledge is produced. Part of understanding "the nature of science" entails understanding the relationship between scientific and technological progress. One common belief is that science creates knowledge and technology applies it. But this is an oversimplification. Scholars who study scientific progress, both historically and philosophically, describe a much more complicated and nuanced story. Science itself is deeply technological.

If science transforms the built world to produce knowledge, technology begins with knowledge and produces material artifacts; it "realizes" ideas in the world. To create useful, reliable scientific insights, these two processes must happen simultaneously, in a back-and-forth dance. Andrew Pickering's *The Mangle of Practice* details how technical and design work in the laboratory are as necessary to scientific progress as developing scientific models.* As scientists improve their tools and techniques for creating phenomena or taking measurements, their understanding of technologies co-evolves with their understanding of the natural world.

In the mid-1800s, physicists Hippolyte Fizeau and Léon Foucault made a series of non-astronomical measurements of the speed of light. Their initial experimental design involved a light source and a faraway mirror, with a spinning toothed gear between them. One of the most difficult problems with the measurement—and a primary source of uncertainty in the results—was entirely technical: they needed a motor that could spin with a precisely known rotational speed. Foucault enlisted the help of Louis François Clément Breguet—a watchmaker turned physicist—to develop an improved fixed-speed motor. Later iterations of the motor apparatus allowed them to make increasingly accurate and precise measurements.

Indeed, many important contributions to science are technical rather than purely theoretical. For example, the Davenport Motor (the first DC electric motor built in the U.S.) was made by the blacksmith Thomas Davenport who, with little formal education, made use of a connection between electricity and magnetism that hadn't been theorized. Likewise, the helical model of DNA could not have been developed without Rosalind Franklin's work on X-ray crystallographic imaging techniques. And consider the discovery of the Higgs Boson at the Large Hadron Collider (LHC). This massive technological undertaking involved thousands of scientists and engineers. A fraction of the team developed particle theory; many more built detectors, developed computational algorithms, or figured out how to cool the LHC's superconducting magnets. It's clear we need to broaden our view of science practice to include work with and development of technology.



Teaching science and technology together, at last

As standards have pushed to have science education reflect the authentic processes of science, they have incorporated "practices" as a way of learning about the world and developing scientific knowledge. But many science classroom practices emphasize talk—through discussions, argumentation, and literacy, including reading and writing about science. It is equally important to consider how students' engagement in science practice can develop their technical knowledge and technical skills.

So how should science education change as the modern world changes? We need a model of science education that can effectively respond to technological change as well as new demands for teaching about technology. We should look for opportunities to integrate science and technology education in ways that are complementary, where the use of technology is integrated into science practice in authentic ways, and where technical knowledge is valued as a product of scientific activity.

Integrating science and technology learning

Scientists often use specialized hardware and software to work with systems for data acquisition and control. The hardware consists of electronics that connect to and sample voltages or currents from connected sensors and turn those into numerical readings. The software (like the popular LabVIEW) controls the sampling, processing, and storage of these data, as well as the actuation of connected devices—for instance, to drive a piezoelectric crystal or a current through a heating or cooling device. These systems can be used to collect experimental data, create experimental conditions, or control an experiment.

Our InSPECT research project, funded by the National Science Foundation, focuses on integrating science and technology learning by creating tools for data acquisition and control. The project engages students in using these technologies to do more authentic experiments involving data collection and analysis. InSPECT makes use of custom-made sensor hardware for creating data, and a LabVIEW-like programming environment for data processing, visualization, and storage, and for the logical control of actuators. Students use these scientific tools to make measurements and analyze data, and learn about computing and sensor hardware at the same time.

InSPECT developed a three-week curriculum investigating the biological processes in plants and animals that produce or remove carbon dioxide from the atmosphere. Throughout the curriculum, students use our custom Dataflow data acquisition and control hardware and software to do several hands-on laboratory experiments to investigate photosynthesis and cellular respiration (Figure 1). They use sensors to measure CO_2 levels in the atmosphere and in controlled environments, while programming LED lamps to turn off and on to stimulate photosynthesis (Figure 2).

The instructional sequence was designed such that students learn about science and technology in parallel. We wanted students to engage in authentic science practices to develop their understanding of biology, learn about modern sensor-based technologies including Internet of Things (IoT) sensor devices, and gain technical skills in programming for data collection and control. Four underlying design principles guided our work.

Using dual learning progressions. Each activity has two sets of learning goals, one about science practices and content and another about the technology. For instance, students are first introduced to the topic of carbon dioxide in the atmosphere when they inspect graphs of CO_2 levels from their classroom. They observe features of the graphs—when the Internet shut down, when the custodian was in the room, when students were in class. This helps them start to think not only about carbon dioxide and where it comes from and where it goes, but also about all the other things that sensors can "make visible" about the world around us.

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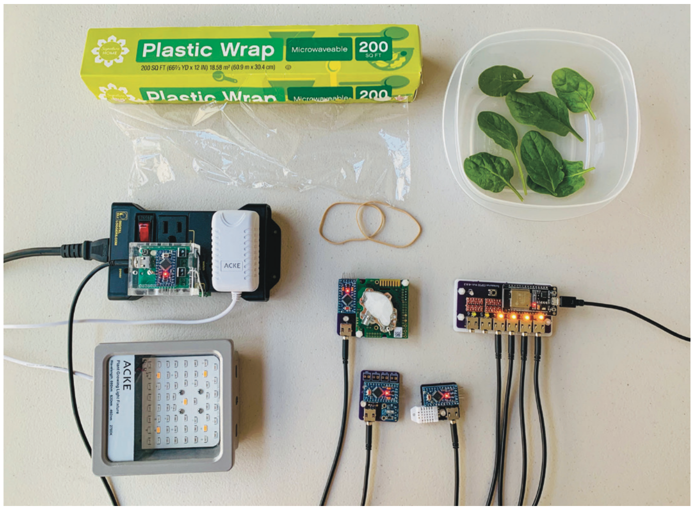

Figure 1. A Dataflow hardware kit including (from top left): plastic wrap, a container of spinach leaves, a custom-built "IoT" sensor hub, carbon dioxide, light, and temperature/humidity sensors, an LED grow light, and an IoT relay.

Introducing sensors as technology. After seeing graphs of the classroom CO_2 levels, students make their own measurements. They notice that their sensors all have different CO_2 readings of the classroom, which creates an opportunity to discuss sources of variation in measurement and issues of accuracy and precision. When learning to control actuators, they use the technology to create automatic alarms that turn on when the CO_2 in the classroom reaches unhealthy levels. When experimenting with the hardware during free time, many students built their own "smart devices," such as an automatic nightlight or a "clapper."

Redesigning hands-on labs to problematize measurement. In contrast to most sensor-based labs, InSPECT labs give students opportunities to learn about the technology they're using to produce their data. For example, the sensors—and their limitations—become central to a redesigned respiration lab, in which students devise ways to measure the concentration of carbon dioxide in their breath both before and after exercise. However, the concentration of CO_2 in undiluted breath is much higher than the sensors can measure directly. Students learn more about what the sensors actually measure and how, then design their measurements around these limitations. For instance, some popped small balloons of exhaled breath into a larger bag of air, while others blew through a straw above the surface of the sensor.

This variation in methods is an indication that students are engaged in scientific thinking about experimental design themselves. And when they then use the sensors to create their own data, they begin to wonder more about them: How do the sensors work inside? How fast can they make measurements? What else might affect the values I see?

Modifying hands-on labs to include programming and control. After a series of activities in which students come to understand photosynthesis and respiration in plants and animals as processes that produce or consume carbon dioxide, they create a final project that puts both their scientific and technical knowledge to use. Students design a way to stabilize the carbon dioxide levels in a closed "ecosphere" container. Some students programmed a light to turn on when the CO_2 levels in the ecosphere are too high; the plant matter inside then photosynthesizes and the CO_2 levels dropped. In this way, students are introduced to scientific practices of using technology to control experimental variables. Depending on how they set up their system and their program, they saw different behaviors of their CO_2 control system.

Conclusion

During classroom observations, we have witnessed students get inspired by the technology. This shouldn't surprise us—just like the natural world, technology in the built world can be fascinating. While technology education has its own purpose and goals, learning with and about technology can also serve as an onramp to science practice.

For science and technology integration to work, students must be able to learn about the technologies they use to create scientific knowledge. To ensure that these technologies are relevant to modern work and life, we should leverage connections between scientific tools and the "everyday" technologies in our modern world. The InSPECT project builds on the synergy between the tools used for data acquisition and control and the technologies underlying modern IoT devices (systems of sensors, computers, and actuators). We are excited by the potential of technology integration in the science classroom to foster creativity and competencies, along with both scientific and technical knowledge.

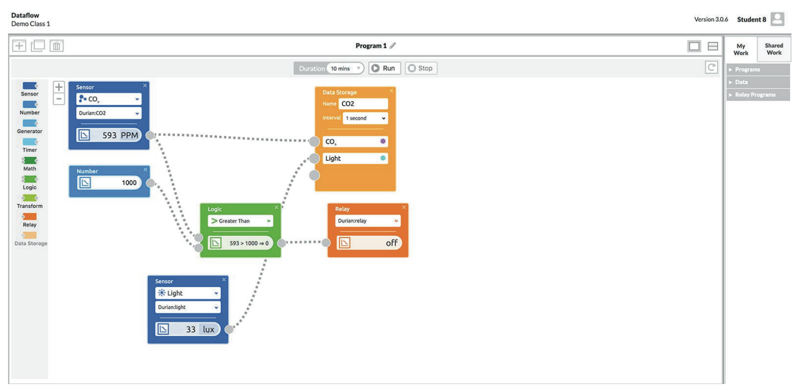

Figure 2. A Dataflow program created by a ninth grade biology student. The program actuates a red-blue LED lamp connected to a relay, and stores and graphs CO_2 and light data during the experiment. When CO_2 levels in the container reached above 1,000 PPM, the student's lamp turned on, initiating photosynthesis in the spinach leaves, which then caused the CO_2 levels to decrease.

* Pickering, A. (2010). *The mangle of practice: Time, agency, and science.* Chicago: University of Chicago Press.

LINKS

InSPECT
concord.org/inspect

Monday's Lesson:

When Disaster Strikes

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By Trudi Lord

The Earth is always quaking and shaking. Movement of Earth's tectonic plates causes approximately 20,000 earthquakes around the globe each year. Fortunately, most earthquakes are so small that they go unnoticed, but some are large and dangerous. Major earthquakes, like the recent ones in Iceland, often make the headlines, even halfway around the world. Students are understandably intrigued and can come to science class with lots of questions. Why do quakes always seem to happen in the same locations? Are we at risk for an earthquake?

Our Seismic Explorer data visualization tool plots earthquakes on a map of the Earth, allowing students to see both large and small earthquakes, compare recent seismic activity to the past, and examine plate boundaries. The data in Seismic Explorer, including the location, depth, and magnitude of each earthquake, from the U.S. Geological Survey, is updated daily. Use Seismic Explorer to investigate earthquakes from 1980 to the present, or focus your inquiry on more recent quakes.

1 Open Seismic Explorer

Go to https://seismic-explorer.concord.org

Run the model and watch as earthquakes are displayed on the world map.

To narrow down the timeline to seismic activity in the last month, click the "Only display recent activity" checkbox, which sets the model to show the last 30 days. Click the "Data Type" menu to view earthquakes, volcanoes, or both (Figure 1). Run the model again.

2 Find the earthquake

When the model is running, colored dots representing earthquakes appear. As shown in the online key, the size of each dot represents the magnitude (size) and the color represents the depth of the earthquake's epicenter. To locate a specific earthquake on the map, switch to Street in the "Map Type" menu to identify countries and zoom into areas of interest. Drag the sliders on the timeline to focus on a time range.

3 Discover patterns

Ask students to think about the location of the earthquake under study. Is it on land or in the water? Is it near other earthquakes? Note that 30 days of data may not be enough for students to observe the telltale lines of earthquakes and volcanoes that reveal plate boundaries. Deselect the recent activity checkbox and run the model again to show over 40 years of activity. Turn on volcanic eruptions to look for patterns in both earthquake and volcanic activity, explore the edges of plates, and think about connections to nearby landforms.

4 Dig deeper

Ask students to identify the type of plate boundary nearest to the earthquake by taking a closer look at the location and distribution of earthquake dots. The depth of earthquakes provides evidence for

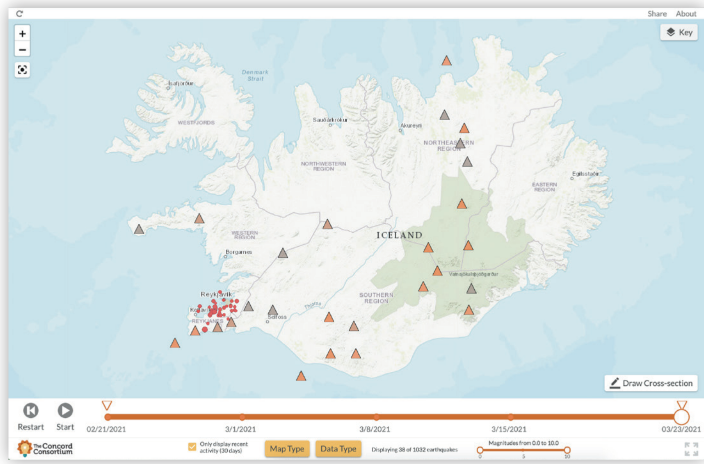
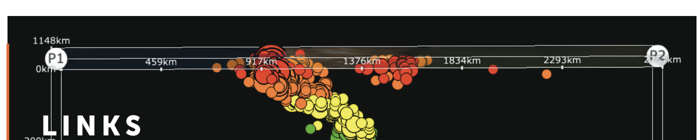


Figure 1. Earthquakes are represented as circles, volcanic eruptions as triangles.

the type of plate boundary at that location. Draw a cross-section to investigate earthquakes both at and below the surface. Notice the diving pattern of earthquakes from shallow to deep at a subduction zone or the multiple surface earthquakes at a divergent boundary. To verify the locations of plate boundaries, check Plate Boundaries in the "Data Type" menu, then use the key to identify boundary types (convergent, transform, and divergent).

Looking for more?

Created by our Geological Models of Exploration of Dynamic Earth (GEODE) project, Seismic Explorer has been embedded in a two-week plate tectonics curriculum unit for middle and high school classes. Students explore data about plate boundaries, make connections to Earth's past, and make predictions about what Earth may look like in the future.



LINKS

GEODE – concord.org/geode
Plate Tectonics – learn.concord.org/geo-platetectonics
Seismic Explorer – seismic-explorer.concord.org

Everything Happens for a Reason:

Developing Causal Mechanistic Reasoning of Plate Tectonics

By Amy Pallant and Hee-Sun Lee

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Our planet's surface is in constant motion. Large pieces of Earth's crust and upper mantle, known as tectonic plates, continually move toward and away from each other at a rate of millimeters to centimeters each year. Over geologic time, their relative motions determine everything from the types of boundaries they form to the distribution of rocks and landforms on Earth's surface and the location and frequency of earthquake and volcanic eruptions (see "Monday's Lesson" on page 7). Plate tectonic theory, the organizing paradigm that revolutionized geosciences, describes the plate and mantle system and is used to reason about how plate movements and interactions can explain where geological phenomena occur and why Earth looks the way it does. The goal of our National Science Foundation-funded Geological Models for Exploration of Dynamic Earth (GEODE) project is to help students use plate tectonics as an explanation for the landforms and geological phenomena observed on Earth's surface.

To consider how plate movements are responsible for shaping and reshaping Earth's surface over time, it's best to think about plate tectonics as a system. The tectonic plate system includes both plates and the mantle, the layer of solid rock that lies between Earth's surface and the molten core in Earth's interior. Always in motion, the mantle acts as a major driver of the system.

Understanding this dynamic system helps us to explain everything from the mid-ocean ridges to the location of the continents and the appearance of Earth's topographical features such as mountains and volcanoes. This systems thinking also gives us the ability to speculate about what changes might happen in the future.

Plate systems thinking

Systems thinking is the ability to think about the whole, rather than merely the parts. With the plate system, this means recognizing that what happens at one plate boundary is affected by and affects what happens along other boundaries on Earth, and that those plates are deeply coupled with the movement of rock in the mantle. Typically, we teach about plate motions along individual boundaries, focusing on convergent, divergent, and transform boundaries in isolation. However, we can better understand the distribution of features and phenomena by looking instead at the entire system.

Take, for example, the boundary found along the Mid-Atlantic Ridge in the middle of the Atlantic Ocean. At this divergent boundary, two tectonic plates are moving away from each other. As they do, magma from the mantle is added to the plates, causing them to get bigger. This phenomenon is known as seafloor spreading. The new plate material is warm and less dense than the rest of the plate. As the plate material cools, it gets denser and is pulled down and away from the ridge.

Meanwhile, convection currents move the mantle below the plates (Figure 1). The mantle is solid rock that is flowing, very slowly, like thick asphalt. It is under high pressure and is heated near the core. As the warmer mantle rock rises, it also cools, eventually pushed away by warmer rising materials and sinking back towards the core. Some of the mantle rock melts and is added to the plates along the boundary. The rest of the mantle flows below the plate, carrying the plates with it. The North American Plate is carried westward and away from the Mid-Atlantic Ridge, pushing into the Pacific Plate, thus shrinking it. Where the plates meet, additional interactions characteristic of the specific boundary types occur.

Plate tectonics system explanations

Our focus on the tectonic plate system builds on research characterizing various stages of a learning progression associated with plate tectonics. Findings from research by our partners at Pennsylvania State University suggest that the way students currently learn plate tectonics leaves them with disconnected concepts, leading to a plateau in understanding. For example, when students learn about individual plate boundaries, they have difficulty transitioning from a single boundary to the concept of a plate bounded by other plates, which all interact on all sides. This research guided the development of our interactive models, curriculum, and assessment materials.

To investigate whether or not students are developing a systems perspective of plate tectonics, we are examining student explanations for geological phenomena observed on Earth. For instance, how well can students explain the formation of the Andes Mountains or the Mid-Atlantic Ridge in terms of the underlying entities of the tectonic plate system—the plates and mantle—and the processes that occur as a result of activities the entities engage in at particular locations over long periods of geologic time?

We have developed a framework to analyze students' written explanations, based on three key features.

- **Entities** are objects that comprise a system.
- **Properties** are well-defined characteristics of each entity.

- **Activities** are a series of actions and interactions produced by entities that result in changes observed over time. These actions are related to the different properties of the entities at a given location and time.

In the plate tectonics system, an expert mechanistic explanation—that is, an explanation that includes system causes and effects—should (1) identify the major entities (the plates and mantle), (2) assign and use the properties of the entities, and (3) articulate their activities (plate movements and interactions along different boundaries) in order to describe how mantle circulation, coupled with plate movement, results in phenomena observed on Earth's surface, such as earthquakes, volcanic eruptions, and landforms.

We assess student understanding in two-part questions, with a multiple-choice component followed by an explanation. Below is an example of one multiple-choice question. Table 1 contains sample student explanations for their choices to this question, as well as our analysis of their explanations based on the entities-properties-activities framework.

Which of the following caused the separation of Africa and South America?

(1) Earth's gravity
(2) Earth's magnetic field
(3) Heat currents beneath the surface
(4) Earthquakes and volcanoes
(5) Wind, waves, and erosion

Student explanations help us glean a bit about what they understand regarding the underlying plate system and the causal mechanisms responsible for why Earth looks the way it does. As students become better able to describe the tectonic system, the more they are able to reason about different aspects of the dynamic Earth system they encounter in later geology units.

Why do volcanoes form where they do? How does the sea floor spread? Why do earthquakes occur at depths along convergent boundaries? How is rock formation related to tectonic environments?

Our goal is to help students develop causal mechanistic reasoning using the plate tectonics system, which can answer questions like these—and other questions they may have about our extraordinary planet.

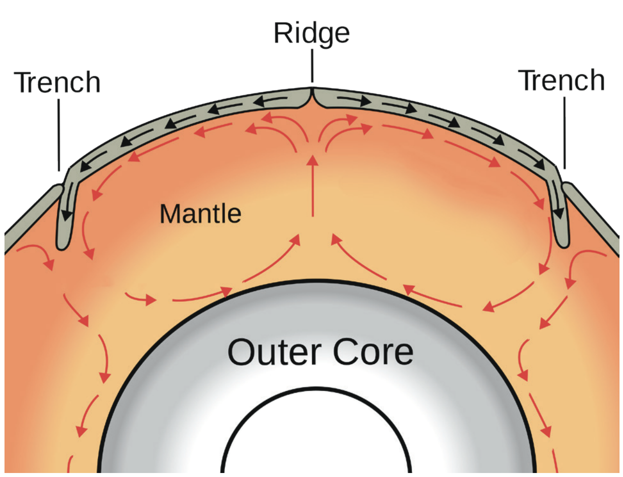

Figure 1. Mantle convection drives the motion of Earth's plates. Modified image created by Surachit. CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0/).

Table 1. Student explanations for the choice they made to the multiple-choice question and analysis of selected responses through the framework of entities, properties, and activities of a plate tectonics system.

STUDENT RESPONSE	ANALYSIS
I think earthquakes and volcanoes cause the continents to move because in order for the earthquakes and volcanoes to occur there would have to be plates that are diverging and converging under the surface of the earth.	Though the student identifies the entities (plates) and the activities (converging and diverging), the student is clearly demonstrating reverse causality from the consequences (earthquakes and volcanoes phenomena) to plate motions, a misconception often seen in plate tectonics reasoning.
The core heats rock, pushes it up and causes plates to move with it. So hot rock being pushed up beneath the earth's surface caused the continents to move with them over millions of years.	This student shows a simple mechanistic understanding, mentioning "hot rock" and "pushed up beneath the earth's surface" as the activity moving the plate (an entity). The consequence of this activity is observed as the movement of continents over millions of years.
It is because the plates form those landforms to happen.	This student identifies the entities (plates), but does not include properties or activities. The consequences of the activities are described as landforms.
The heat currents make them [plates] move because when the crust cracks the magma comes up from the mantle pushing things out of the way and creates land which forces the plates to move.	This student includes both plates and magma as entities, and describes the activities that result both at and below the surface.
Because what moves the plates are movements in the mantle which are caused by heat currents because when the material near the bottom of the mantle gets heated by the core it becomes less dense and rises then the currents are separating near the crust pulling the crust apart by the heated material getting cooler, then becoming more dense causing gravity to pull down hard on it then going to the bottom near the Earth's core becoming heated again and repeating the process.	This student includes clearly identified entities, properties of the entities, and activities responsible for the phenomenon. The answer describes how the heated mantle (entity) gets less dense (property) and rises, separating the crust (activity). It describes how materials cool (property) over time and are pulled down by gravity because they are denser (property), pulling the plate along with it (activity).

LINKS

GEODE
concord.org/geode, learn.concord.org/geo-platetectonics

Share and Share Alike:

New tools for tracking and supporting knowledge co-construction in mathematics classrooms

By Leilah Lyons, Merve N. Kursav, Alden J. Edson, and Chad Dorsey

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Mathematics assignments are primarily designed to demonstrate the individual performance of learners, who are often discouraged from working with one another. "Borrowing" ideas from another student's work becomes "cheating." For over 30 years, the Connected Mathematics Project (CMP) has been working to turn that idea on its head.

According to CMP, mathematical knowledge is best discovered through co-constructing mathematical concepts with one's peers. In CMP classrooms, learners work together in small groups to solve problems and derive mathematical principles that can be shared with the class. The dividends from this kind of teamwork are manifold—from gaining meaningful collaboration experiences to mastering deeper mathematical knowledge. But it can be difficult for teachers and students to unlearn years of conditioning that says "sharing is cheating."

The Concord Consortium and Michigan State University have been developing the Collaborative Learning User Environment (CLUE) to support the sharing of mathematical artifacts. By logging all student actions, CLUE also provides detailed information about learner sharing behaviors. We are researching indicators of knowledge co-construction in CLUE, and hope that by exposing teachers and learners to these indicators we can shift social norms, changing the "social infrastructure" of the classroom to embrace sharing and co-construction activities.[1]

Defining co-construction as artifact sharing

CLUE emulates the small group work in CMP classrooms by providing all learners with individual workspaces, where they can create mathematical artifacts, plus import them from the curriculum, groupmates' workspaces, or documents published by the teacher or other classmates (Figure 1). While CLUE does not support *direct* artifact co-construction (as when multiple learners edit a shared Google document), it permits indirect co-construction through artifact *sharing*. For example, a teacher can share a table of data with the class or urge an individual student to publish a creative exploration of a mathematical problem. Learners are strongly encouraged to borrow (i.e., copy) artifacts they find helpful in constructing solutions in a "bricolage" style approach rooted in constructionist and constructivist theories of learning. This cross-pollination allows ideas to spread within groups and across the classroom as concepts get developed.

Defining indicators of artifact sharing

Social Network Analysis (SNA) studies how people connect to one another, for example, via social media. In an ideal co-construction scenario, we would expect to see group members sharing with one another *frequently*, where the sharing is *distributed* evenly (i.e., learners are not left out) and is *reciprocated* (more than one learner is the source of artifacts). We explore these metrics in the CLUE environment, noting that researchers have found other SNA metrics to be more or less reliable for studying collaborative learning.[2]

Frequency of sharing as a relative comparison

One group of learners shared artifacts 15 times over a 40-minute class—a frequency of 0.375 per minute. Is this a lot or a little? Does the teacher need to intervene to encourage more sharing or not? To acquire meaning, a frequency reading must be defined relative to another frequency reading (e.g., relative to the problem, other groups, or the group's own sharing behaviors over time), and teachers may want to examine frequency in different ways depending on their goals (e.g., gauging whole class performance on a problem or flagging groups for sharing behaviors).

Table 1 shows data from two 7th grade groups of learners engaged with three different CMP investigations. Based on tallies, it seems that Group B shares artifacts half as much as Group A on Investigation 1. If we look at percentiles, Group B is in the 80th percentile, a rank they maintain for Investigation 2. But by the third investigation, Group B has dropped its sharing by 4. Group A has also dropped, by 3. Is this difference just as meaningful for both groups? Group A is still in the 95th percentile for Investigation 3, while Group B is in the 60th percentile (down from the 80th). A within-group examination shows that for Group A, it is a 20% drop in their average sharing, following a 68% gain between Investigations 1 and 2, a net 40% gain; for Group B it is a 114% drop, following a 57% drop between Investigations 1 and 2, a net 171% loss and noteworthy trend. The different ways frequencies can be examined can suggest different conclusions about when and how to intervene.

	Investigation 1	Investigation 2	Investigation 3
Sharing Event Counts			
Group A	11	21	18
Group B	6	4	0
Across-Group Percentile of Sharing			
Group A	90%	95%	95%
Group B	80%	80%	60%
Within-Group Change in Sharing			
	Average Sharing	Δ Investigations 2 & 1 (% change)	Δ Investigations 3 & 2 (% change)
Group A	14.75	10 (68%)	-3 (-20%)
Group B	3.5	-2 (-57%)	-4 (-114%)

Table 1. Data from two groups of learners engaged in three CMP investigations.

Distributed sharing: Density and isolates

Density is a common SNA metric that measures distribution by dividing the number of observed connections by the number of possible person-to-person connections. Unfortunately, it can mask loners and super-contributors. For example, Group C has a density of 1.0 for Investigation 1, suggesting that the sharings are evenly distributed among group members, but in fact one of the group members was left out. Conversely, Group D has the highest density for that investigation (D=1.5), but 15 of the group's 18 sharings originate with the same super-contributor student. Density measures need to be augmented with extra information, such as "loner alerts," and a way to indicate if sharing is unidirectional or reciprocated.

Misleading reciprocity

In SNA, reciprocity quantifies how many of the connections between people are bidirectional. This can detect sharing imbalances (e.g., where only one student's work is being copied), but it can mislead. Figure 2 shows the sharing behaviors of two groups. There are more reciprocal relationships in Group E (two) versus Group F (one), and the number of reciprocations is the same in both groups (three). But traditional measures of reciprocity, which gauge the distance from purely symmetrical reciprocation, would give Group F a higher reciprocity.*

Instead, we must compute the reciprocity of mutually sharing dyads separately from the non-reciprocity of non-mutual dyads, as combining these phenomena renders any group rankings meaningless. We defined a reciprocity measure, Small Group Mutual Arc Reciprocity (SGMAR), that calculates mutual reciprocity and conditions it on the proportion of mutual dyads within the group, which better characterizes mutual sharing relationships. We also defined an Unreciprocated Arc Ratio (UAR) that measures the proportion of total sharing acts that were not part of a mutual dyad. Group E and Group F have an SGMAR of 0.25 and 0.17, and UAR of 0.22 and 0, respectively. These values allow group rankings in terms of "relationship building" versus "one-way copying."

Conclusion

Doing mathematics is inherently a social and collaborative activity. Many assumptions underlying SNA make applying it to artifact sharing in small collaborative groups challenging. But by bringing a sensitivity to how teachers (and possibly learners) might use this information, we can adapt SNA metrics to reveal intriguing student sharing phenomena. The next step is to work with teachers to determine how this information might shape their practice and how they would prefer to receive and view the information (e.g., via filters, rankings, or visualizations such as heatmaps). Our ultimate goal is to design interface features that help expose the value of shared learning activities and make clear to teachers and students alike that in a CMP classroom, copying isn't considered cheating. Borrowing is an important part of knowledge co-construction.

* Using Arc Reciprocity, the value would be 1 versus 0.5; using Garlaschelli and Loffredo's definition, it would be 1 versus 0.76.

1. Bielaczyc, K. (2006). Designing social infrastructure: Critical issues in creating learning environments with technology. *Journal of the Learning Sciences*, *15*(3), 301–329.

2. Saqr, M., Viberg, O., & Vartiainen, H. (2020). Capturing the participation and social dimensions of computer-supported collaborative learning through social network analysis: Which method and measures matter? *International Journal of Computer-Supported Collaborative Learning*, *15*(2), 227–248.

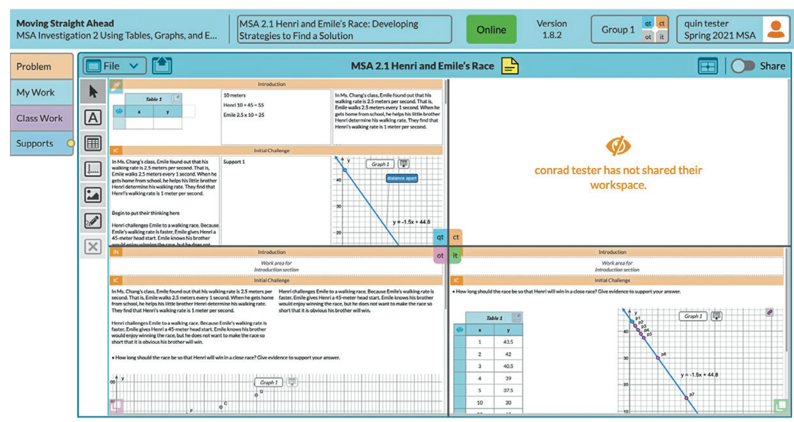

Figure 1. The "four-up" CLUE display shows the workspaces of all four groupmates, with the student's own workspace in the top left. Learners can switch between this view and a singular view. Curricular materials as well as student- and teacher-published documents are accessible through the tabs to the left.

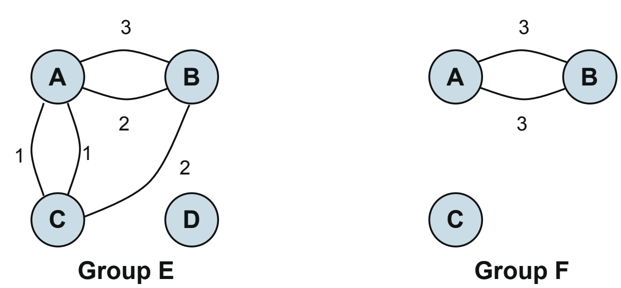

Figure 2. The sharing behaviors of two groups of students in the same class.

LINKS

Digital Inscriptions
concord.org/digital-inscriptions

Technology-Enhanced Assessments for NGSS Classrooms

By Dan Damelin and Cynthia McIntyre

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Let's say your state has adopted the Next Generation Science Standards (NGSS). You've learned the *lingua franca* of three-dimensional learning and can speak fluently in acronyms: DCIs are the disciplinary core ideas, CCCs the crosscutting concepts, and SEPs the science and engineering practices. You're thoughtful about implementing content-rich activities in your classroom, looking for opportunities to engage students in authentic practices such as asking questions and defining problems, planning and carrying out investigations, or analyzing and interpreting data, all while attuned to linking to structure, systems, patterns, or one of the other crosscutting concepts. But with such a robust description of science learning embodied in the NGSS, how, you wonder, can you assess student understanding with evidence that students are building proficiency toward NGSS performance expectations (PEs)?

To address this challenge, the Next Generation Science Assessment (NGSA) Collaborative has developed technology-enhanced science assessment tasks, rubrics, and accompanying instructional resources for elementary and middle school classrooms that are enacting NGSS-aligned instruction. Assessment tasks are available for Grades 3–5 in physical science, life science, and Earth and space science and for the middle grade band (Grades 6–8) in life science and physical science.

The NGSA Collaborative was founded by researchers and technology developers at the University of Illinois at Chicago, WestEd, Michigan State University, and the Concord Consortium (SRI International was also involved in early work). This core group has developed and continues to develop the middle school tasks. A subset of the collaborative, joined by the UChicago STEM Education group, is actively engaged in elementary task development. This work is supported by grants from the National Science Foundation, the Chan Zuckerberg Initiative, and the Gordon and Betty Moore Foundation.

Developing assessment tasks

How do we assess success in reaching NGSS performance expectations? Assessments should measure knowledge-in-use through the integration of the three dimensions of learning specified by the NGSS, and they must, by definition, include student *performance*. Because science practices are an essential component of each NGSS performance expectation, new ways of thinking about assessment item design are critical.

The Next Generation Science Assessment middle school and elementary teams are in the process of completing over 200 individual assessment tasks. We start by identifying a PE or related cluster of PEs and unpacking the associated NGSS dimensions (DCIs, CCCs, and SEPs). We then create a mapping of these components to formulate Learning Performances (LPs). Like the performance expectations from which they are derived, LPs are three dimensional but represent a smaller target for assessment than the often quite broad NGSS PEs. Multiple LPs together provide guidance regarding student progress toward an individual or small cluster of PEs.[1] For instance, for the PE *MS-LS1-6 Construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms*, we created five LPs (see page 13).

Because engagement in scientific practices can be greatly facilitated through technical affordances, we carefully consider during the task design process where technology can best be applied to achieve the task assessment goals. Tasks are offered in an authoring and delivery platform the NGSA Collaborative helped to develop and include embedded computational models, videos, and data analysis tools, plus drawing and other modeling tools to facilitate student demonstration of their understanding. We review the tasks for scientific accuracy, equity, and fairness, and pilot them with students in classroom and lab settings. They are then published to the NGSA task portal.

Technology-rich tasks

On the NGSA task portal, for example, one can find a cluster of PEs focused around kinetic and potential energy encompassing the following middle school PEs: MS-PS3-1, MS-PS3-2, and MS-PS3-5. The first of eleven LPs associated with this cluster of PEs is "LP KE01: Students construct and interpret a graphical display to describe the proportional relationship of kinetic energy to the mass of a moving object." One of the tasks created for this LP, titled "Zach's Toy Car,"[2] provides a video for students

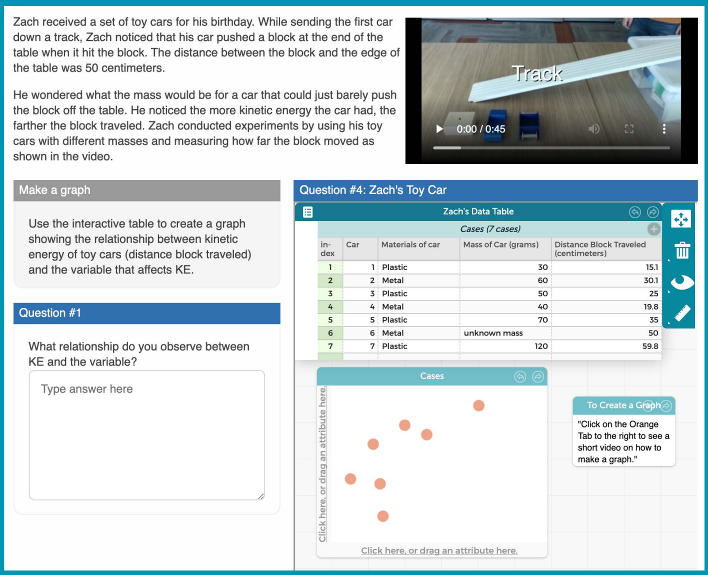

Figure 1. The "Zach's Toy Car" middle school task allows students to construct and interpret a graphical display to describe the proportional relationship of kinetic energy to the mass of a moving object.

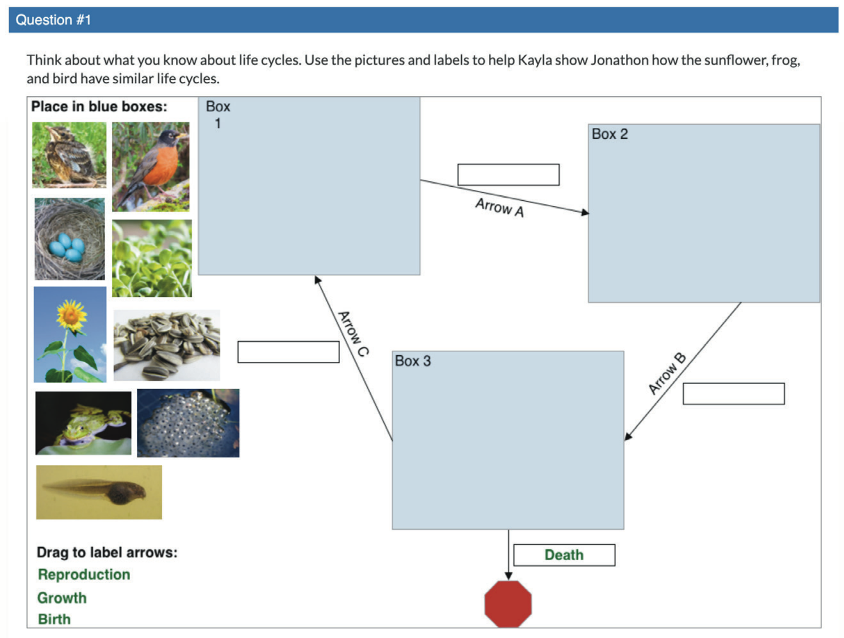

Figure 2. The "Sunflowers, Frogs, and Birds: Create a Model" elementary school task offers students a customized tool to create a model illustration of their conceptual understanding of the life cycles of various organisms.

to experience the phenomenon of a toy car rolling down a ramp, along with experimental data of the mass of the car and the distance a block positioned at the end of the ramp moves when hit by the car (Figure 1). An embedded data analysis and visualization tool allows students to quickly generate graphs of the data and interpret data to solve a problem.

At the elementary level for the NGSS performance expectation 3-LS1-1, which is centered around life cycles, we developed two LPs, the first of which is "LP 3-L01: Students develop or revise a model to show similarities in the life cycles of different plants and animals, using patterns they have identified."[3] A task for this LP, titled "Sunflowers, Frogs, and Birds: Create a Model," offers students a customized tool to create a model illustration of their conceptual understanding of the life cycles of various organisms (Figure 2). The model building tool provides students an opportunity to express their understanding beyond the traditional task of writing.

The tasks are available on the NGSA task portal.[4] We hope that this extensive set of assessment tasks and the process we use to develop them inspires others, so that more students have opportunities to demonstrate their understanding of the three dimensions of the Next Generation Science Standards and teachers can make informed decisions about next steps in working with their students to achieve their learning goals guided by the NGSS.

1. For more information about our task development process see http://nextgenscienceassessment.org/design-process
2. https://authoring.concord.org/activities/10601
3. https://authoring.concord.org/activities/11566
4. Assessment tasks are free to use and are licensed under the Creative Commons Attribution-NonCommercial 4.0 (CC BY-NC 4.0) license, which means you're welcome to copy, distribute, and display them as long as you attribute the Next Generation Science Assessment project and do not use them commercially.

Photosynthesis

Performance Expectation

MS-LS1-6. Construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms.

Learning Performances

LP P01: Students *analyze and interpret data* to determine whether plants and other photosynthetic organisms grow with the input of energy from sunlight.

LP P02: Students *analyze and interpret data* to determine whether plants and other photosynthetic organisms take in water, carbon dioxide, and energy (e.g., sunlight), to produce food (sugar) and oxygen.

LP P03: Students *develop a model that shows* that plants (or other photosynthetic organisms) take in water and carbon dioxide to form food (sugar) and oxygen.

LP P04: Students *evaluate how well a model shows* that plants and other photosynthetic organisms use energy from the Sun to drive the production of food (sugar) and oxygen.

LP P05: Students *construct a scientific explanation* for how plants (and other photosynthetic organisms) are able to use energy and matter from the sugar they produce to grow and support their other necessary (life-supporting) functions.

LINKS

Next Generation Science Assessments
ngss-assessment.portal.concord.org

Under the Hood:

A New Engine for Modeling Biological Processes

By Sam Fentress

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Consider a tiny hormone as it flows between cells and binds to a receptor protein in a cell's membrane. The protein, if working correctly, triggers a series of reactions that releases a signal molecule headed for the cell's nucleus, which in response produces a strand of mRNA. This mRNA finds its way to the endoplasmic reticulum, where it causes melanin to be packed into a tiny organelle called a melanosome. The little bundle of melanin gets carried through the cell by protein motors, where it is anchored in the best location to absorb light and darken the cell. All this happens hundreds of times a second throughout this cell and all of its neighbors.

To illustrate such cellular processes for our Geniventure dragon genetics game, we needed to develop a new modeling engine. After deciding not to attempt the impossible task of modeling a cell from physics first principles (like we do with Molecular Workbench), a rule-based agent model seemed like a good solution. However, while a number of agent-based modeling engines exist, from NetLogo to our own Populations engine (which we use to model ecosystems and evolution), none of them seemed to fit the bill. We wanted to make models that looked organic and beautiful, that could be created fairly easily even by non-programmers, and that could be reused to make many different cells without needing to rewrite the same rules each time.

We created a new engine called Organelle with two unique features (Figure 1). First, model environments are created using SVG, a vector-based image format that allows us to draw features of the environment and name them semantically. That is, we can label the parts (Golgi apparatus, microtubule, receptor protein) and refer to them directly in the rules for the agents ("move towards the nearest receptor protein"). Second, we can define agents—the individual moving bodies in the cell, such as proteins and vesicles—and give them rules that can be reused in any other model. So we only have to define, say, a melanosome (the organelle that packages melanin) once, and it will behave the same way in other models, though the presence of new features or other agents may cause it to behave differently.

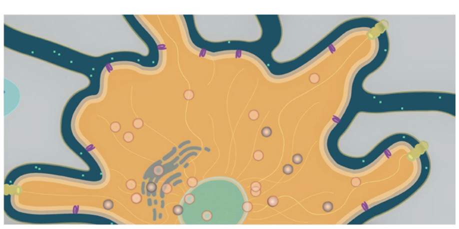

Figure 1. An Organelle model of a cell producing melanin.

To create the rules for these agents, an author describes their behavior using verbs that are meaningful for the kinds of models we are creating: "grow," "flow," "diffuse," "follow," "find," etc. The aim is to create a readable set of instructions that can be understood even by a non-programmer. (These verbs can be expanded by a plug-in system to allow programmers to create all kinds of behaviors.)

A sample set of rules written in YAML can be seen in Figure 2. The code instructs the model to spawn a new "hormone" agent every 20 model ticks at one of the SVG elements named "intercellular-path," if any exist in the current model. Once spawned, this agent will simply follow that path until the end, where it will be removed from the model. Naturally these rules can become much more complex.

Our open-source Organelle engine is also used in our Connected Biology project, which links genetics and evolution, but it can be used for more than cellular models—the engine can work anywhere agent-based models can benefit from semantically defined environments and simple, portable rules. Find demos of these models and try modifying them by editing the rules directly in the browser at the Organelle homepage.

```yaml
name: hormone
image: assets/hexagon.svg
properties:
  speed: 1.2
spawn:
  every: 20
  at:
    selector: "#intercellular-path"
    which: random
initialState: flowing
rules:
  flowing:
  - follow:
      selector: "#intercellular-path"
      which: nearest
      finally:
        die: true
```

Figure 2. Sample set of rules, written in human-readable YAML language, instructs our Geniventure model.

LINKS

Organelle engine
organelle.concord.org

Innovator Interview:
Steve Roderick

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It makes so much sense to think of the world in terms of accumulations, rates of flow, and feedback. It simplifies things.

As a biology major at Boston University, Steve planned on becoming a marine biologist. After spending his junior year in New Zealand and Australia, studying crown-of-thorns starfish on Heron Island, he thought he was one step closer to that goal. But a mix-up with college credits changed everything.

To recoup some lost credits, he enrolled in a summer course called AESOP (Arts and Environmental Science Outline Program) that met on a barge behind the New England Aquarium. The professor invited local professionals to share their work and serve as mentors for student-created projects. When someone from Jay Forrester's group at MIT presented his work on systems dynamics, Steve was hooked. "This was 1971, the year *The Limits to Growth* was published," he recalls. "I was totally enamored."

During the summer with Forrester and his team of graduate students, Steve realized it was not just systems dynamics that fascinated him, but also the approach to teaching he was experiencing through the AESOP program. Following college graduation, Steve taught environmental education courses outdoors, then did a one-year stint filling in for a biology teacher on maternity leave before moving to Cali, Colombia, to teach chemistry and math at an international school.

After returning to the U.S., Steve completed a master's degree in biology and environmental policy at Tufts University, before beginning a thirty-year teaching career at Lincoln-Sudbury High School, where he ultimately became the science department chair. He's especially proud of an environmental issues elective he created. "We basically would just do projects around town," he says, starting at the Conservation Commission to find out what was needed—from certifying vernal ponds to lobbying for wildlife corridors. His students had access to a forest and river near the school, but Steve also found opportunities to get to the sea, taking them on field trips to Nahant and Plum Island.

While teaching, he kept in touch with Forrester and was always looking for ways to bring systems thinking to his high school classes. In 1996 he spent a sabbatical year at MIT, where he took classes with systems scientists John Sterman and Jim Hines at the Sloan School of Management. He notes, "It makes so much sense to think of the world in terms of accumulations, rates of flow, and feedback. It simplifies things."

Steve is now part of the group developing our SageModeler systems modeling tool. Building static equilibrium models, he says, is extremely intuitive for students. "Teachers like having their kids visualize their thinking about something complex and the way it works." But he admits that making the leap to thinking dynamically can be a big challenge.

Steve is also helping teachers on the InquirySpace project bring more authentic science experiences to their classes. He was thrilled to hear a teacher describe her students' "a-ha" moments using CODAP to "move data all around" because he recognizes the power of that to inspire other teachers. "When you see a teacher get excited, the eyes of other teachers light up." It's all part of a system with feedback loops.

He hopes to instill that awareness of systems to connect things, people, and ideas in students. "I fundamentally believe that science education should include the study of how science intersects with social issues. Systems is a great way to do that." He continues, "It's our world. We have to understand that everything we do has ramifications elsewhere."

When Steve retired from teaching in 2016, he joined the Concord Consortium. He also bought a sailboat. Having learned to sail during summers at his grandfather's beach house in Fairhaven, Massachusetts, he now laughs, "This is me being a kid again." And he still dreams of becoming a marine biologist.

The Concord Consortium
25 Love Lane, Concord, MA 01742

COVID-Inspired Data Science Education through Epidemiology

The ongoing COVID-19 pandemic is providing an unprecedented amount of health and social science data, and serves as a compelling starting point to engage in data science activities. A new project funded by the Innovative Technology Experiences for Students and Teachers (ITEST) program at the National Science Foundation is designed to empower young people to understand data science through epidemiology. The COVID-Inspired Data Science Education through Epidemiology project partners include Science Education Solutions, Tumblehome, STEM Next/Imagine Science, Strategic Learning Partners for Innovation, Jackson Laboratory, Partnerships in Education and Resilience, and the Concord Consortium.

The project engages 400 underserved youth across the country in "Data Detective Clubs" that meet in person or online. Fifteen hours of out-of-school activities are based on *The Case of the COVID Crisis*, a young adult adventure novel by former Concord Consortium board member Pendred Noyce. The novel follows two curious and determined middle school students, Clinton and Mae, on a time-travel adventure guided by a teenage mentor from the future. They visit epidemics of the past and present, including measles, smallpox, Nipah, the 1918 flu, Ebola, and COVID, and travel to the Congo, Bangladesh, Taiwan, Pittsburgh, and Navajo country. While the topic is the spread of disease, the narrative shares historical facts that abound with the power of science—and *data science*—and the hope for cures. Each chapter is accompanied by a podcast of the characters discussing data, followed by activities designed to explore real datasets using our Common Online Data Analysis Platform (CODAP). Students also watch animations about viruses, vaccines, and clinical trials.

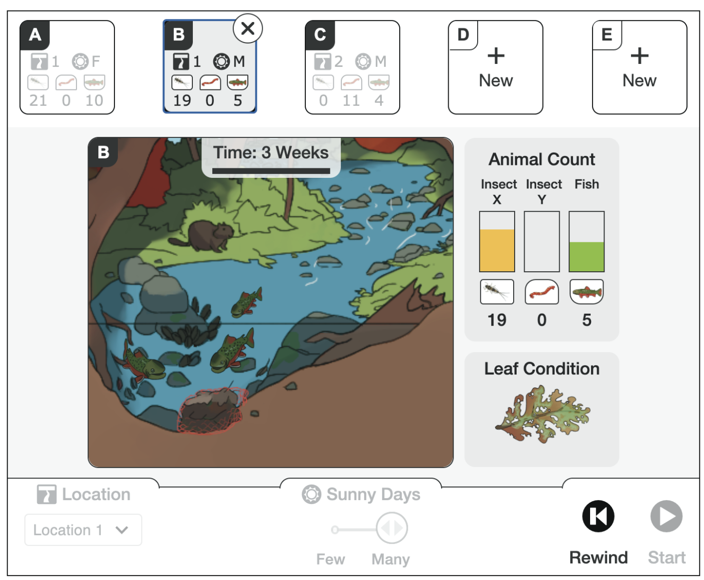
The ITEST program supports projects that contribute to increasing students' knowledge and interest in science, technology, engineering, and mathematics (STEM) and information and communication technology (ICT) careers. In order to encourage youth interest in a myriad of data-rich careers in epidemiology, the project provides opportunities for students to meet data scientists, researchers, and/or local epidemiologists either in person or virtually.

Project research studies how youth use datasets and data tools to ask epidemiological questions, examine patterns, and make predictions; explores how youth become motivated to engage in work at the intersection of data science and epidemiology; and examines the affordances of data clubs that integrate narrative, inquiry-based data activities, accessible data tools, animations, and career exploration.

New Assessments in Massachusetts

The Massachusetts Department of Elementary and Secondary Education (DESE) is developing a series of innovative science assessments for Grades 5 and 8 as part of the state's emphasis on more authentic learning experiences that are rigorous, engaging, and culturally relevant for all students. The Concord Consortium was part of the DESE assessment development team, which also included Pearson and WestEd.

The goal of the new approach to science assessment is to measure student learning and promote more equitable access to high-quality science instruction. Innovative assessments measure student knowledge of disciplinary standards and provide a deep measure of students' mastery of the science and engineering practices in the state's Next Generation Science Standards-inspired science frameworks. Assessment items include a new type of performance task for students, in which they engage with longer computer-based science activities or simulations to conduct investigations, create and explore models, and solve science or engineering problems. A small number of schools will begin piloting the assessment in spring 2021 while the rest of the state will continue to use the existing Massachusetts Comprehensive Assessment System (MCAS) for science and technology/engineering.



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