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The Concord Consortium

Perspective:

Improving STEM Education with Next Generation Science Standards

By Chad Dorsey

These are exciting times in education. Public awareness of the need for science, technology, engineering and math education is rising, and new STEM initiatives are beginning across the nation. In this issue, we welcome one of the most important events in this new awareness of STEM, the release of the Next Generation Science Standards (NGSS). These new standards highlight important new dimensions for science education and present many opportunities for technology to aid teaching and learning.

The importance of these new standards and their heritage should not be underestimated. The NGSS have been a long time in coming, and are grounded in the National Academy of Science's thoughtful and important *Framework for K-12 Science Education*. Together, these documents signify a new and influential direction for STEM education. They elevate the importance of Earth science, present engineering education as coequal with science education for the first time and emphasize a key set of Scientific and Engineering Practices and Crosscutting Concepts that should buttress all learning in these disciplines.

Our true call as a nation is to prepare a world of future scientists, engineers and citizens who are fluent in the way science and engineering are performed. Students must possess the ability to do science and engineering—this is the key to unlocking deep student learning and is essential to building a nation of literate citizens and an innovative, competitive workforce. Technology holds great power to build such understanding.

These pages provide numerous examples of how the NGSS—and especially its Practices and Crosscutting Concepts—are central to our work in STEM education at the Concord Consortium. Over nearly two decades, we've been demonstrating how technology can make complex concepts more approachable, underscore important crosscutting ideas and engage students in the practices of science and engineering.

Scientific and engineering practices

One of the most important practices of science and engineering is the design of investigations for exploring and answering testable questions. Scientifically accurate models and simulations provide a ripe proving ground for such experimentation, making investigation possible in areas that could otherwise never be explored. And probeware such as motion detectors, temperature sensors and other devices for recording data extends students' senses and permits them to see multiple representations of their surroundings unfold in real time.

Models and simulations

Models are key to understanding, exploring and expressing almost all concepts in science and engineering. Even paper or drawn models of objects or systems can have great utility in the classroom. However, in many cases, technology opens significant new opportunities for learning, especially about processes that occur very quickly or slowly or phenomena that happen on scales too large or small to observe easily.

Atomic and molecular processes are at the core of practically all physical phenomena, yet they remain invisible and mysterious. Modeling software such as our Molecular Workbench brings these hidden processes to light and makes them fully explorable. A solid understanding of geological processes is essential for comprehending everything from climate change to resource extraction. Models and simulations like those in our High-Adventure Science curriculum shed important light on these complex and otherwise invisible concepts. And through the use of our Energy2D and Energy3D software, students can design virtual houses and examine their thermal efficiency, placing virtual heaters and adjusting the angle of the sun's rays coming through windows. This use of virtual representations permits students to design solutions more quickly while actively integrating the process of engineering design with the underlying scientific principles that define its natural constraints.

Actively using models and simulations can help students build understanding and convey ideas. Molecular Workbench addresses this need by permitting students to design and modify their own models to represent physical scenarios and then test their ideas. Students can develop a firm understanding of the relationship between genes, observable traits and DNA mutations by using one of our genetics models to design and perform their own investigations. Students gain an appreciation of how natural statistical variation influences inheritance patterns.

Models are especially powerful at engaging students in the process of science, by helping them understand how to generate and test predictions based on their growing scientific understanding.

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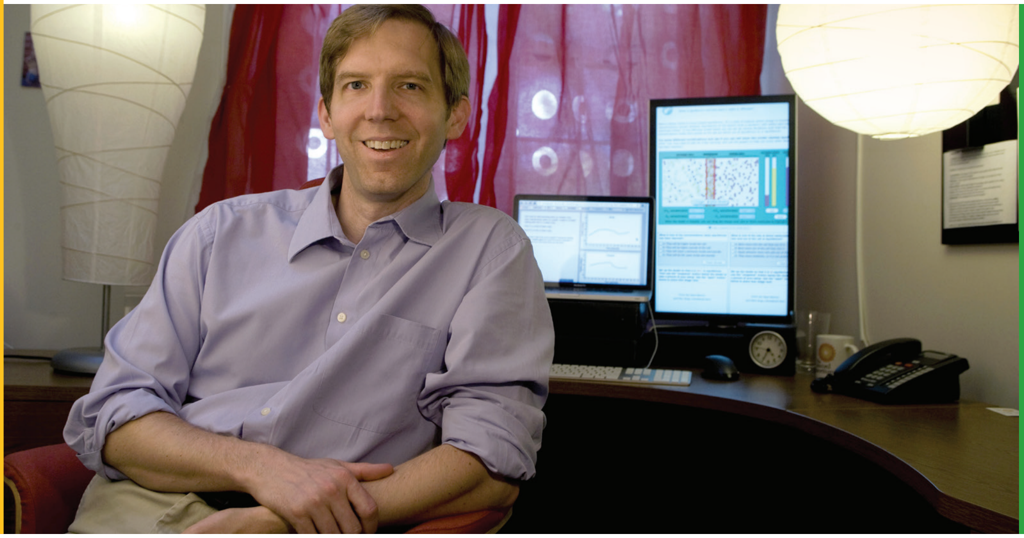
The NGSS hold the potential for helping focus the current national concern for improving STEM education.



(Scientists in all disciplines leverage the predictive power of computational models.) And models help build understanding about scientific concepts. When students confirm predictions with models and simulations, a classroom comes alive with motivating "a-ha" learning moments. A model that does not confirm a student's prediction as expected is equally important; the student must incorporate new ideas to reconcile the unexpected behavior.

Probes and sensors

Investigations of phenomena in the real world can also be enhanced in meaningful ways through the use of technology. Probes and sensors make acquisition of real-time data quick, accurate and straightforward and permit students to explore everything from the complex motion of objects to the intricate thermodynamics of chemical reactions. The instant feedback such devices provide allows student investigations to center on core ideas rather than on tedious experimental setups. Technology opens the way for students to perform multiple experiments within a short time, evolving their understanding through experimentation and discovery. And when the physical world and the world of models and simulations merge—such as in our work with mixed reality—technology adds an important layer of visibility to real-world investigations, augmenting student understanding of physical processes in exciting new ways.

Crosscutting concepts

Technology-rich curricula can help students build a nuanced picture of their world by emphasizing crosscutting concepts for science, math and engineering education. Using standardized representations in engaging and structured opportunities for exploration, technology can present phenomena in such a way that crosscutting concepts are highlighted across domains.

Students can use technology to navigate across multiple scales in space and time, gaining an in-depth appreciation for science's dynamism and interconnectedness. Using technology, students can also engage with systems and system models to a depth that no other medium can accommodate, and explore cause and effect in new ways.

Models and simulations provide striking, manipulable views of intangible concepts such as cycles, conservation of energy and matter or the intricate connection between structure and function. Technology makes ideas like stability and change accessible to students—often for the first time. They find themselves able to manipulate aspects of a system to understand its intricate balances and truly comprehend ideas such as change over time, equilibrium and dynamic feedback loops.

The NGSS hold the potential for helping focus the current national concern for improving STEM education. They will undoubtedly help bring clarity and unity to the patchwork of state standards that has developed throughout the standards movement in the past decades. We hope they will be seen as a new opportunity to find the most effective ways to approach STEM education on a national scale. As this occurs, innovative educational technology will be a critical component in this STEM education revolution.

At the Concord Consortium, we remain hard at work providing opportunities for revolutionary digital learning in science, math and engineering. With the advent of new learning standards, the need for this work becomes more pressing. We're excited to continue innovating in these areas, and we invite you to join us in exploring their promise further.

Molecular Workbench and the New Standards

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By Robert Tinker and Chad Dorsey

The Next Generation Science Standards (NGSS) raise many challenges for science teaching and learning. The standards ask teachers to cover fewer science ideas in more depth than currently while placing far greater emphasis on crosscutting concepts and science practices. Making these changes requires new content, pedagogical techniques and tools. Powerful computer-based tools like Molecular Workbench can address these challenges by allowing students to learn from their own investigations how a simple set of core concepts can explain a wide range of observations that cut across fields and disciplines. This can build student understanding of science practices, crosscutting themes and core ideas all at the same time.

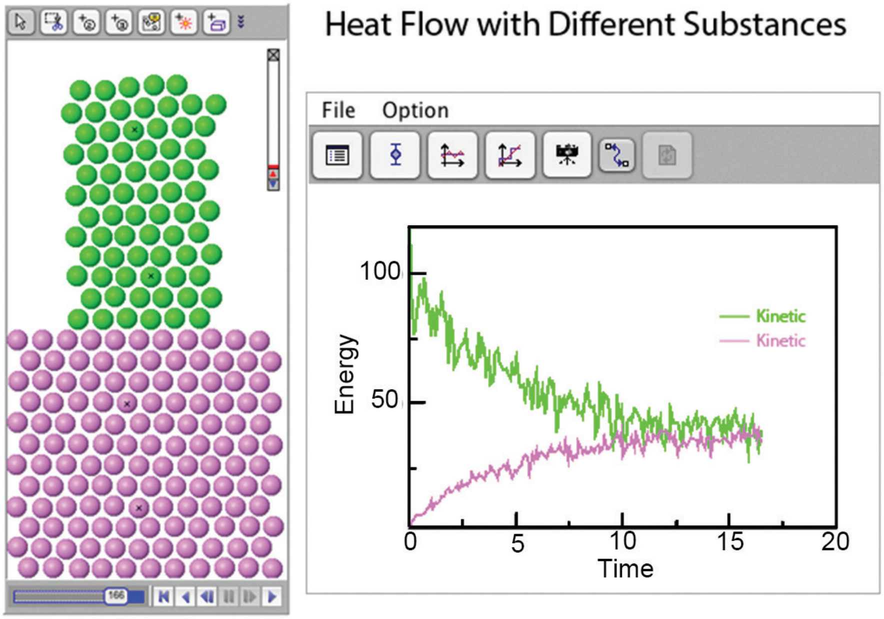


Figure 1. Molecular Workbench models flexibly demonstrate concepts such as the effect of atomic mass on thermal conductivity.

Molecular Workbench

Funded by the National Science Foundation and Google.org, Molecular Workbench is a powerful and versatile cluster of open-source resources for modeling atomic-scale interactions and exploring their macroscopic effects. Every Molecular Workbench model is based on a general **physics engine** that calculates the forces acting at the atomic level, adds rules for photons, chemical bonds and macromolecules, and applies Newton's laws to determine the resulting motion. When the interactions of hundreds of atoms are computed this way, collective behavior emerges that can illustrate macroscopic effects as varied as phase change, diffusion and explosions.

The Molecular Workbench is also a **model maker** that can create hundreds of different models. Having students use this capacity to modify models or make their own is a great way to learn. For example, a teacher could challenge students to explore the effect of atomic mass on thermal conductivity (Figure 1). Or, using the online user manual, students can make simple models themselves, the best way to understand the underlying science.

But most learning activities need more than just a model; they require background information, instructions and assessment items, all of which can be created with the **activity maker**. Figure 2 shows pages from a biotechnology activity and an activity on spectroscopy, which illustrate how Molecular Workbench provides these authoring capabilities.

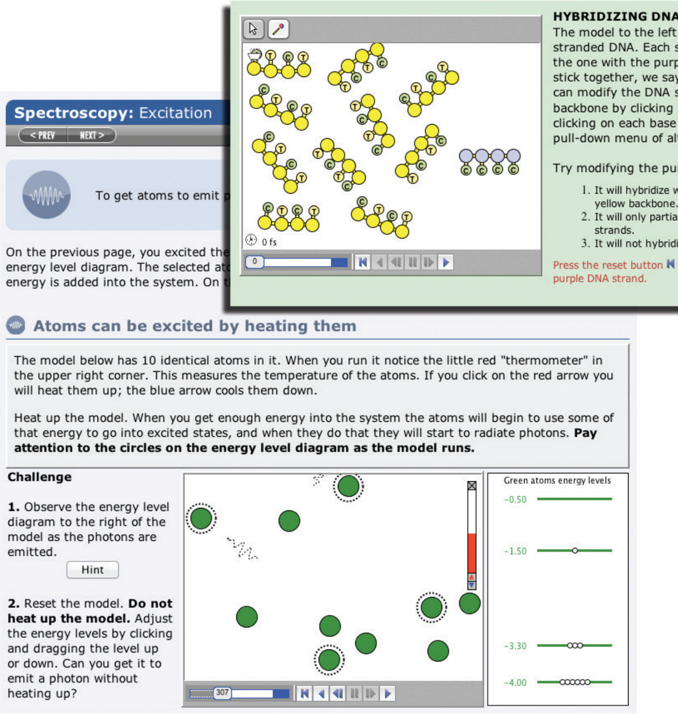
Molecular Workbench is also a **component maker**. It can be converted into applets and scripts that are easy to incorporate into other platforms and run entirely in Web browsers. Many of our models are used in the University of California, Berkeley's WISE projects (Figure 3). The browser-based Next-Generation Molecular Workbench extends MW's flexibility to more mobile devices and simplifies integrations even further (Figure 4). Easy to embed and share, these JavaScript models are being used by MIT in an edX Massive Open Online Course, embedded in Data Games, a data exploration tool from KCP Technologies, and included in online textbooks and supplements.

Scientific practices

By running models and observing many runs under different conditions, students gain important insights into the underlying processes. Figure 1 shows a simple model that can be used to explore factors affecting heat flow between different substances. Students can observe the transfer of energy caused by interactions between atoms and see a real-time graph of the temperature. Careful study of the model can expose details such as thermal equilibrium and the relative contributions of mass and velocity in the kinetic energy of individual atoms.

This model, as with most Molecular Workbench models, is suitable for a wide

(continued on p. 6)



HYBRIDIZING DNA

The model to the left contains a bunch of single stranded DNA. Each strand is identical except for the one with the purple backbone. If two strands stick together, we say they have hybridized. You can modify the DNA strand with the purple backbone by clicking on the button and then clicking on each base (*i.e.* letter), bringing up a pull-down menu of alternate nucleotide choices.

Try modifying the purple DNA strand so that:

1. It will hybridize with the other DNA strands with the yellow backbone.
2. It will only partially hybridize with the other DNA strands.
3. It will not hybridize at all with the other strands.

Press the reset button each time you want to modify the purple DNA strand.

To get atoms to emit p

On the previous page, you excited the energy level diagram. The selected at energy is added into the system. On t

Atoms can be excited by heating them

The model below has 10 identical atoms in it. When you run it notice the little red "thermometer" in the upper right corner. This measures the temperature of the atoms. If you click on the red arrow you will heat them up; the blue arrow cools them down.

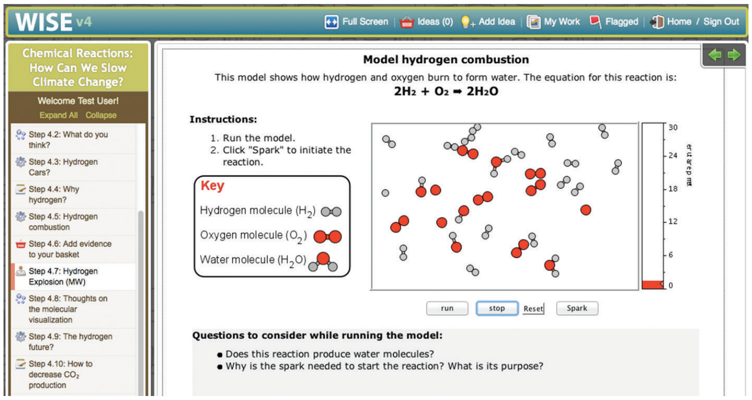
Heat up the model. When you get enough energy into the system the atoms will begin to use some of that energy to go into excited states, and when they do that they will start to radiate photons. **Pay attention to the circles on the energy level diagram as the model runs.**

Challenge

1. Observe the energy level diagram to the right of the model as the photons are emitted.

2. Reset the model. **Do not heat up the model.** Adjust the energy levels by clicking and dragging the level up or down. Can you get it to emit a photon without heating up?

Figure 2. MW delivers scores of activities complete with instruction and embedded assessment that help make concepts such as hybridization (inset) and light-matter interactions accessible.



Model hydrogen combustion

This model shows how hydrogen and oxygen burn to form water. The equation for this reaction is:

$$2H_2 + O_2 \rightarrow 2H_2O$$

Instructions:

1. Run the model.
2. Click "Spark" to initiate the reaction.

Key

Hydrogen molecule (H_2)
Oxygen molecule (O_2)
Water molecule (H_2O)

Questions to consider while running the model:

- Does this reaction produce water molecules?
- Why is the spark needed to start the reaction? What is its purpose?

Figure 3. A hydrogen combustion MW model, integrated here with the WISE Chemical Reactions activity, presents a dynamic demonstration of energy conservation.

(continued from p. 5)

variety of applications and grade levels. Younger students may gain great value from simply visualizing how temperature relates to molecular motion and spreads. More advanced students may learn important lessons about equilibrium while higher education students can explore proportionality between temperature and kinetic energy.

Explorations like these based on Molecular Workbench models can be structured to include all eight NGSS scientific practices so students can experience how science is done. And the visual nature of these models helps ensure that students at a disadvantage in language or math skills are not left behind.

Gravity (m/s²) 9.8
Rod Length (cm) 140
Starting Angle (°) 45
Mass of the Ball (g) 250
Damping (Newton per m/s) 0.00
☐ Show Velocity Vector?
Angle 37 °

Figure 4. Browser-based Next-Generation Molecular Workbench components can operate on many devices and be easily embedded in alternate learning environments.

Crosscutting concepts

The NGSS also identify seven crosscutting concepts that represent important core ideas encountered across science and engineering. Students need to learn these concepts in context rather than in isolation. Molecular Workbench is ideal for understanding them in ways that further deep learning.

Figure 2 (inset) shows a Molecular Workbench activity containing a model of hybridization, a technique frequently used in biotechnology. Students can observe that random motion breaks up any pairing of the four-group molecules unless they have complementary charges. Experimenting with this model shows vividly that at too low a temperature all molecules pair at random, while at too hot a temperature none pair. This brief interaction demonstrates three crosscutting concepts at the same time: it highlights a *cause and effect* interaction critically entwined with the inherent *stability* of a system at the heart of a biochemical process relating *structure and function*.

Because of the variety of physical models within Molecular Workbench, teachers can easily find many examples in which crosscutting ideas can be applied to appropriate STEM concepts. A teacher might choose to focus on models with very different content, all of which can be understood by applying energy conservation. The models in Figure 2 and 3 illustrate this idea.

Figure 2 also shows an activity in which atoms can have quantum states of various energies (when an atom is in an excited state, a dashed circle appears around the atom). Students discover that these excited states can be caused either by collisions between atoms or by photons (short, wiggly lines). Once excited, the atoms can transfer their excitation energy—in quantified packets—either through collisions or by emitting a photon. Thus, energy is converted between kinetic energy, excitation energy and light energy, and is conserved in each instance. These ideas can be applied to a wide range of topics, including spectra, fluorescence, lasers and LEDs.

The atoms in Figure 3 can make and break chemical bonds. Since it takes energy to break a bond and that same energy is released when a bond is made, energy is again conserved, but converted between types of energy. In this case, the conversion occurs between chemical and kinetic energy. In the figure showing the reaction that produces water from H_2 and O_2, this simple idea is applied to explosions. The mixture of these two gases is stable because a bond must be broken before H_2O can be produced, but a tiny spark that breaks only one bond can initiate a chain reaction, rapidly consuming all the oxygen and hydrogen—the atomic view of an explosion. Starting with these models the crosscutting concept of energy conservation can be applied to a wide range of chemical phenomena: catalysis, polymerization, net energy of a reaction, reaction pathways and partial reactions.

Conclusion

The strength of Molecular Workbench is the engine that computes the evolution of a few basic laws into complex systems. The degree to which Molecular Workbench can support large portions of the Next Generation Science Standards suggests that a small collection of such powerful modeling tools could revolutionize science instruction. Someday, a few computational models similar in power and flexibility to Molecular Workbench will address topics such as heat transport, evolution, geophysics, astronomy, engineering design, quantum mechanics and fluids to support learning across the entirety of the Next Generation Science Standards.

LINKS

Molecular Workbench
http://mw.concord.org

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Monday's Lesson:

Seeing Heat Transfer

By Carolyn Staudt and Edmund Hazzard

> ***"When I observe my students in traditional lab experiments versus simulated investigations online or a combination of the two, it's evident that deeper connections are made with this generation [of students] when technology is utilized. It's how they're used to learning."***
>
> — Jennifer Aytes, 10th grade teacher, Kansas

Imagine if you could see the temperature of every surface in your house as a moving, colorful collage—red for hot pockets and currents of air, blue for cold, plus yellow and orange for rising and falling temperatures. This would allow you to follow the transfer of heat through the materials and the motion of warm and cold air throughout the building.

Our computational models allow you to do just that and more. They render dynamic heat flow with brightly colored temperature gradients, vectors and isothermals for both solids and fluids (Figure 1). Energy2D* is the only available heat transfer simulation that combines scientific accuracy with ease of use, making it perfect for STEM (science, technology, engineering and math) education. Students can create heat sources, walls, windows, sunlight and wind, and adjust the properties of the materials. And with all that colorful data at their fingertips, imagine the questions you could ask—and answer—about heat and heat transfer.

Developing and using models

The Next Generation Science Standards (NGSS) call for students to develop and use models as an essential scientific and engineering practice. Engineers use models to predict and test the designs of everything from houses and airplanes to bridges and nuclear reactors. Scientists use models to change parameters and explore scenarios—from quantum behavior and evolution to heat transfer and global warming.

Many model types are embedded in short classroom activities in our Innovative Technology in Science Inquiry: Scale Up (ITSI-SU) project, funded by the National Science Foundation. ITSI-SU assists teachers in preparing diverse students in grades 3-12 for STEM careers by engaging them in exciting, inquiry-based science and engineering activities that use computational models and real-time data collection. Teachers can create a class and enroll students in the ITSI-SU portal, then receive reports of all student work.

Engineering, technology and applications of science

In the ITSI-SU middle school engineering activity "Convection in a House," students use Energy2D models to answer the question: How does air carry heat throughout a house? They explore natural and forced convection in carrying heat, as well as the effects on heat flow of blocking air in a two-dimensional house with walls, a roof, windows and a heater (Figure 2). They also measure the wind chill effect, experimenting with the cooling effect of moving air. Finally, students add and move barriers and create openings or closings to allow or block air flow.

The visible effects of these changes on heat transfer are immediate, allowing students to explore multiple variations in order to develop a picture—both intuitive and analytic—of heat flow. And while seeing may be believing, better yet, seeing can lead to understanding, especially when it comes to making the invisible—like heat and heat transfer—visible.

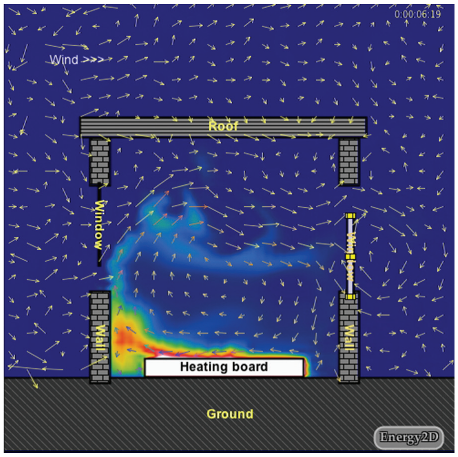

Figure 1. Air circulation on a windy day.

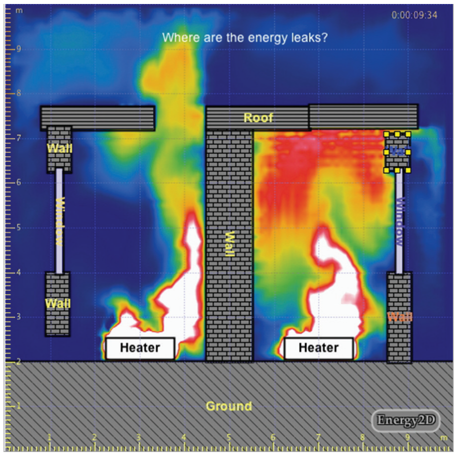

Figure 2. Natural convection in a house with various openings.

Try it out

To preview or run the activity, go to http://itsisu.portal.concord.org/activities#msengineering

LINKS

ITSI-SU
http://concord.org/itsi-su

ITSI-SU portal
http://itsisu.portal.concord.org

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* Energy2D was developed by Charles Xie for the Engineering Energy Efficiency project.

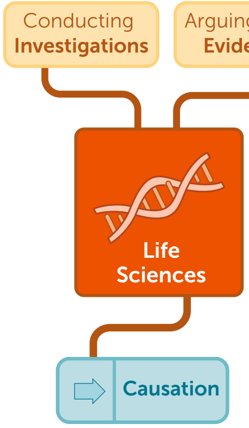
Meet NGSS

with Concord Consortium Activities

The Next Generation Science Standards (NGSS) represent an exciting and important new direction for education in this country. Technology provides many ways for teachers and students to engage with the NGSS more deeply.

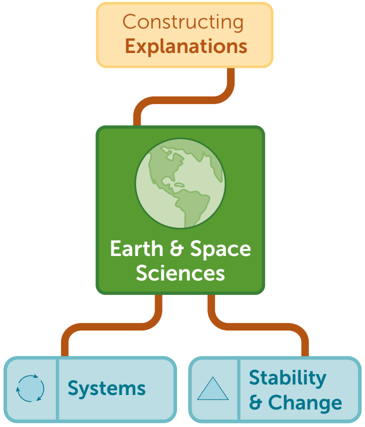
Computational models and probe-based activities bring important learning within new reach. Using such activities, elementary students can watch biological evolution, middle school students can analyze and interpret data to understand the genetic basis of inheritance and high school and college students can argue from evidence in discussing interactions between molecules. With these technology-supported activities, students can engage in doing real science as they plan and carry out investigations, use models, analyze data and design solutions. Students using such technology-based activities also gain wide experience with crosscutting concepts—from scales in space and time to energy and systems—across domains in science, math and engineering.

The NGSS provide a framework and examples, and leave open myriad paths to STEM learning. Our graphic on the back cover demonstrates just a few of the many ways in which the NGSS Practices, Core Ideas and Crosscutting Concepts can be combined into lessons that build enduring STEM understanding. To help get you started on your journey, we've provided a selection of illustrated examples that you can use today. You can find all of these available for free—or find other activities to support your own path—at **http://concord.org/ngss.**



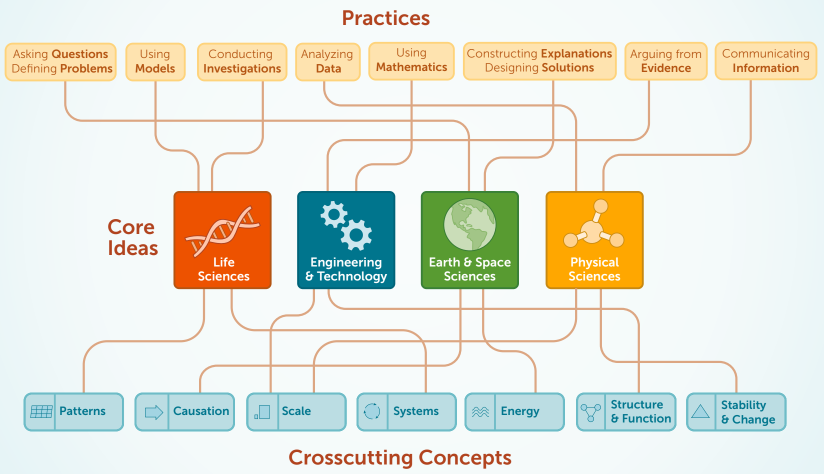
Geniverse

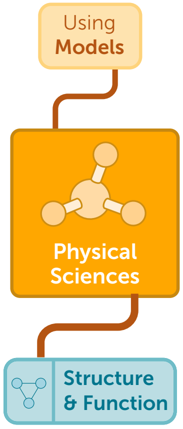
In Geniverse, students interact with a world filled with fanciful dragons and real genetics to learn about the genetic mechanisms of inheritance and the bioinformatics of real-world disease research. Students find themselves in a game-like virtual environment that fosters scientific experimentation. Students breed virtual dragons, examining their genes and studying the traits they inherit. Students use data from these virtual experiments as evidence to create arguments supporting their ideas about how certain traits are inherited. They collaborate as active scientists within their class, discussing results and conducting new experiments to prove or disprove their theories. As the curriculum progresses, students encounter a disease in the dragon population and conduct research within a genetic database to diagnose its cause. By experimenting with models in this open environment, students learn firsthand that biology is an active, experiment-driven science.

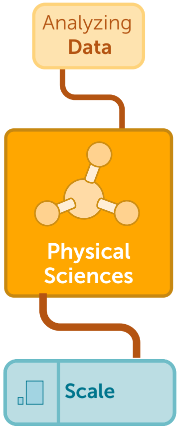


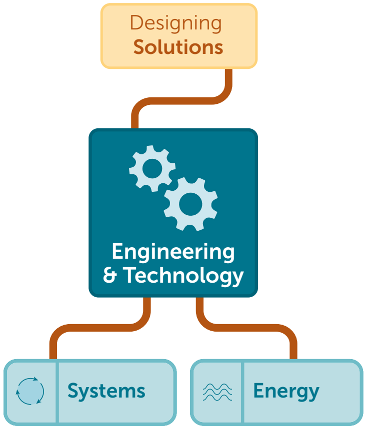
High-Adventure Science

In the High-Adventure Science activity "Modeling Earth's Climate," students examine authentic scientific data and explore in-depth computational models to learn about the effects of different environmental factors on atmospheric temperature. By varying parameters such as CO_2 concentration, surface albedo and amount of exposed seawater, students gain an appreciation for the various systems and feedback loops involved in determining Earth's temperature. Students use this knowledge to make predictions from real-world data and construct explanations for their predictions. Through the process of exploring models and constructing explanations, students also gain important experience with the uncertainties involved in all scientific explanations and predictions.









Next-Generation Molecular Workbench

Through interactive investigations with Molecular Workbench (MW) visualizations, students can learn how a simple set of core concepts can explain a wide range of observations across fields and disciplines. Students grapple early on with the concept that macroscopic phenomena such as states of matter, evaporation and condensation depend upon the underlying nature of matter. MW demonstrates in a highly explorable fashion how the particulate nature of matter provides a coherent explanation for these phenomena. States of matter investigations give way to concepts such as gas laws and their subtleties, nucleation, latent heat and solubility. Molecular Workbench also makes accessible concepts as diverse as quantum mechanics, electronics, DNA, proteins and the mechanisms of photosynthesis. (Pages 4 through 6 provide many more examples of how Molecular Workbench can support student understanding.)

SmartGraphs

Scientists and engineers use mathematics to represent relationships, to enable the prediction of the behavior of physical systems and to identify significant patterns and correlations in data. The use of graphs is an important and ubiquitous feature of this approach. SmartGraphs provide instructional hints and scaffolding to help students make sense of graphs. In the SmartGraphs activity "Describing Velocity," students learn to connect position-time and velocity-time graphs. They analyze real data from a graph of a car's motion and become exposed to the representation of various proportional relationships related to motion. Activities such as this provide students a deeper understanding of concepts such as motion and help students learn to analyze graphs and apply their predictive power to new situations.

Engineering

In our Engineering Energy Efficiency project, students design solar houses to understand the effects of design solutions on energy transfer and efficiency. Using virtual models and our Energy3D customized CAD software, students create solar house designs, then construct and measure their efficiency using real-time data from probes and sensors before redesigning for improvement. Through this process, students are able to approach the iterative design process with increased efficiency and gain a deep, applied understanding of how crosscutting energy concepts play out in real-world situations.

LINKS

Activity Finder
http://concord.org/activities

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The Future of Fracking:

Exploring Human Energy Use

By Amy Pallant

Today few states require Earth science as part of the high school curriculum—despite the fact that both NSES and AAAS Benchmarks have substantial Earth and space science content standards. However, this may change. The Next Generation Science Standards (NGSS) give equal importance to Earth and space science, physical science, life science and engineering. And it's likely that the 26 Lead State Partners that helped develop the standards will adopt them in their entirety, which could provide a significant motivation for incorporating more Earth and space science content into their required curriculum.

When the NGSS are adopted, many more teachers may be charged with teaching the new content. But the subject will likely be new to these teachers and resources scarce. This is where High-Adventure Science comes in. The National Science Foundation has funded the development of an online curriculum for middle school and high school students that covers five Earth systems and sustainability topics: climate change, fresh water availability, energy use, earth resource availability and land use management. Each module includes interactive computer-based models, real-world data and video of scientists currently working on unanswered questions related to the topic.

Energy use

We have already developed two High-Adventure Science curriculum modules on climate change and on fresh water availability. One new module in development will help students think about *where* energy comes from and *how much* energy is used. As the global human population increases, demands for energy increase. To understand the national and international issues that emerge from these energy demands, students must have a basic understanding of energy, energy sources, energy generation, energy use and conservation strategies.

But thinking about energy is complicated. Electricity, for example, is generated by a variety of sources: coal-fired power plants, nuclear power plants, biomass-fired power plants, natural gas-fired power plants, hydroelectric power plants, solar thermal plants, photovoltaics and wind turbines. Humans have managed to harness energy in many ways to power their endeavors, but the production of electricity has effects and consequences.

Our newest module is intended to help students think in terms of energy systems. Our goal is to have students examine how much energy they use, how energy resources are distributed and used globally, and how the quality of life of individuals and societies is affected by energy choices. This is a very big topic—more than students can cover in a one-week module.

One approach, under consideration for the new module, is to look specifically at the intersection of how increases in human population drive the demand for energy resources and how this affects Earth's systems. We are currently focusing on hydraulic fracturing (also known as "fracking"), in which natural gas is

recovered from shale. Between 2000 and 2010, shale gas production in the United States increased dramatically; it now comprises approximately 22% of the total U.S. energy production and is expected to grow further, to an estimated 47% by 2035 (Figure 1). By exploring the future of fracking in detail, we hope that students will see the implications of using natural gas compared to other energy sources, as well as the bigger picture of overall energy use.

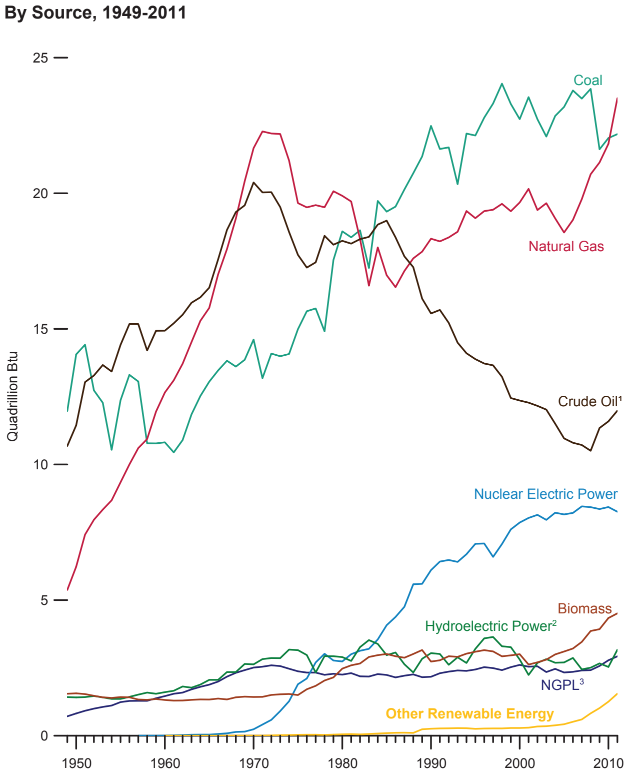

Figure 1. The source of energy for the U.S. is changing. For the first time, natural gas production is now higher than all other energy sources.

Source: U.S. Energy Information Administration (2011).

Addressing NGSS

The new standards take an Earth's systems approach, reflecting the interconnectedness of Earth's different spheres. Human activity on the Earth is also incorporated into the standards, thanks to an increasing awareness of human impact on Earth's surface systems and of the critical role that natural hazards and resource availability play in human society as populations, industrialization and urbanization increase.[*]

For example, *ESS3.A: Natural Resources* states that students should understand that all of the materials, energy and fuels we use are derived from natural sources and their use affects the environment; some resources are renewable over time while others are not; resources are distributed unevenly around the planet as a result of past geologic processes; resource availability has guided the development of human society; and use of natural resources has associated costs, risks and benefits. Additionally, *ESS3.C: Human Impacts on Earth Systems* focuses on the concept of sustainability and emphasizes responsible management of natural resources.

The High-Adventure Science curriculum plans to address these learning goals with activities that prompt students to consider where natural gas is found, what Earth processes occurred to form natural gas reservoirs, how humans get access to energy sources, what they use energy for and the risks and benefits of energy use. Models are ideal for exploring this Earth system and the human interactions with it. Students will be able to explore the effects of fracking in different locations of shale below Earth's surface, see how natural gas is extracted and examine the effects of fracking on contaminating local groundwater. They will also be able to consider how human actions affect both the geosphere and hydrosphere by thinking at the systems level, a crosscutting concept highlighted in NGSS.

By experimenting with interactive models students also gain experience in science practices. The curriculum scaffolds students to ask questions, define problems and engage in argument from evidence. Indeed, a distinctive feature of the High-Adventure Science curriculum is the use of argumentation item sets, which consist of four questions that require students to:

1. make scientific claims
2. explain their claims based on evidence
3. express their levels of certainty
4. describe the sources of certainty

These item sets, used throughout the curriculum, encourage students to reflect on evidence from models and real-world data and to evaluate the certainty of scientific claims. Students have shown significant pre- and post-test score gains on previous High-Adventure Science modules that have been classroom tested. Armed with these essential critical reasoning skills, students will be able to think about sustainability and reducing environmental impacts while improving lifestyles and promoting security for the world's population.

Earth may have a certain resiliency, allowing it to adapt to anthropogenic impacts, but it's clear that Earth's systems are changing under the pressures exerted by humans. It is critical to understand fundamental Earth science concepts as a foundation for analyzing human impact on Earth's systems. The NGSS acknowledge this as an essential principle. High-Adventure Science is providing resources to put these ideas into practice. And with luck and the adoption of NGSS, Earth science will be taught in more of our nation's classrooms.

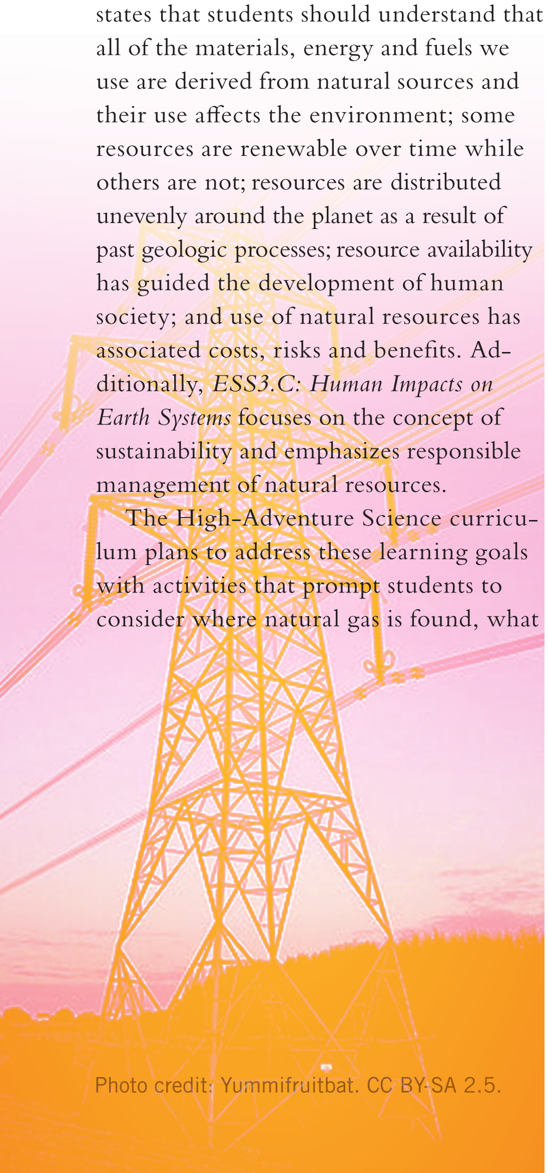

Photo credit: Yummifruitbat. CC BY-SA 2.5.

LINKS

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

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[*] Wysession, Michael E. (2012). Implications for earth and space in new K-12 science standards. *Eos*, 93(46).

Mixed Reality

Brings Science Concepts to Life

By Charles Xie

Charles Xie
(qxie@concord.org) directs the
Mixed-Reality Labs project.

In his *Critique of Pure Reason*, the Enlightenment philosopher Immanuel Kant asserted that "conception without perception is empty; perception without conception is blind ... The understanding can intuit nothing, the senses can think nothing. Only through their union can knowledge arise." More than 200 years later, his wisdom is still enlightening our work in mixed-reality science experiments.

Mixed reality refers to the integration of real and virtual worlds to create new environments where physical and digital objects coexist and interact in real time to provide user experiences that are impossible in either the real or virtual world alone. Perception is a cognitive process that occurs in the real world while conception is a cognitive process that can be stimulated by virtual reality. Mixed reality couples the two processes.

Enacting science concepts in the real world

One way to look at the cognitive potential of mixed reality is to start by examining hands-on activities. Students enjoy hands-on activities because they provide perceptual experiences that feel real. For these experiences to make sense, however, students must be prepared with the conceptual framework needed to understand what they perceive. For example, while conducting an experiment about a gas law, students must be able to reason about the results using the kinetic theory (a gas is made of many interacting molecules in perpetual random motion). In this case, the temperature, pressure and volume of a gas can be perceived, while molecules, their motions and their collisions cannot—these are concepts scientists developed to explain the perceivable properties of gases.

Traditionally, students learn the kinetic theory first and then investigate gas laws in the lab. But integrated learning is not guaranteed. Even if students have studied a concept and performed well on a written test, they can still fall back on their possibly erroneous preconceptions in a lab, as if they had not been taught the concept earlier.

To enhance conceptual learning in lab activities, we can use powerful computers to render abstract concepts as visual, dynamic simulations and use sensors to seamlessly integrate the simulations with perceptual experiences in the real world (Figure 1). Such simulations can respond to changes of physical properties caused by the user's actions. In this way, students can see the science concepts at work in the real world. For example, students can walk around a building holding a tablet that is running a molecular simulation of air and experience how the air temperature they feel is related to the simulated motion of air molecules displayed on the screen. And when a student ventures outside, the tablet can run a simulation revealing how water molecules form a regular lattice structure when the environmental temperature is below the freezing point; that lattice would break when the student walks back inside.

These mixed-reality activities represent a novel method of blending computer simulations into the real world. Simulations capable of reacting to changes in the environment provide a way to translate the otherwise obscure numeric data from sensors into compelling visualizations of science concepts.

Situating computer simulations with perceptual anchors

Another way to look at the cognitive potential of mixed reality is to start with learning with computer simulations. Simulations of invisible properties and processes are now widely used to teach science concepts. However, visual simulations of invisible phenomena alone are often insufficient for learning, because cognition requires a real-world context. For conceptual understanding to take root, students must find ways to connect new concepts to their perceptual experiences and integrate them with their current knowledge.

To help students make these mental connections, instructional designers often contextualize science animations with graphics that represent familiar objects. For example, clicking an image of a bike pump in a gas simulation adds molecules; clicking an image of a Bunsen burner adds heat, and so on. These images serve as the *perceptual anchors* that link the picture of random molecular motion to the everyday experiences of pressure and temperature. These anchors, however, are limited to visual perception.

What if, instead of clicking on images, students could actually exert force or add heat to compress or heat a simulated gas (Figure 2)? This way, the strange simulation can be meaningfully situated in a familiar environment and connected with different kinds of perception (e.g., spatial, mechanical and thermal senses). In this mixed-reality configuration, natural user

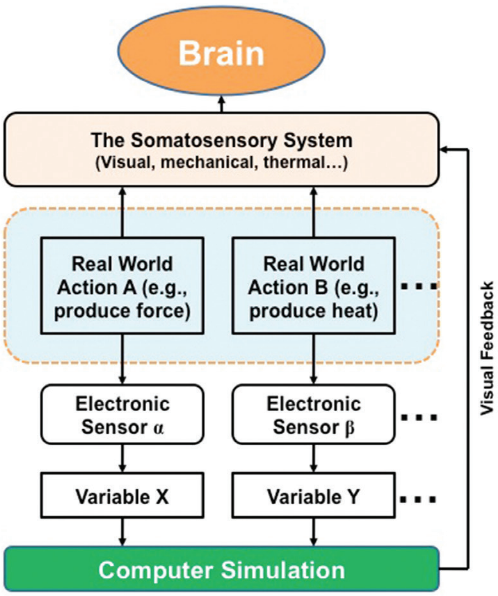


Figure 1. Mixed-reality labs use sensors and simulations to create integrated multisensory learning experiences. Real-world actions result in changes that are simultaneously perceived by both the user and the sensors. Without any delay, the sensors signal the simulation to update the display accordingly, providing instant visual feedback that enhances perception.

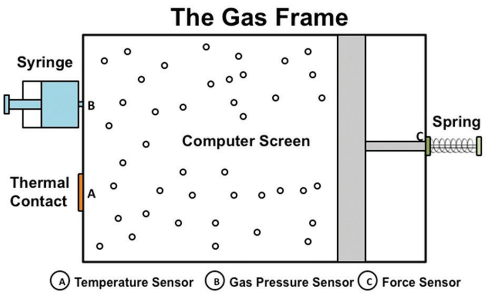


Figure 2. A mixed-reality activity for studying gas laws based on our Frame technology, in which students can "push" or "pull" a virtual piston using their hands, "heat" or "cool" virtual molecules using a hot or cold object and "inject" or "draw" virtual molecules using a syringe.

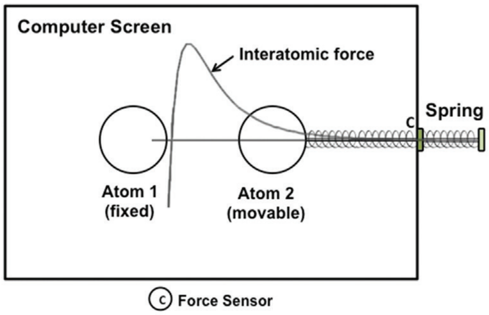


Figure 3. A mixed-reality activity for studying interatomic interactions. Students can push or pull a spring to "feel" the attraction and repulsion force between two atoms.

actions are mapped to variables in the simulation to create an illusion—as if students could physically manipulate the virtual molecules at an extremely small scale.

Students can even "feel" interatomic forces using mixed reality. Figure 3 shows an activity that connects the sense of force with a visualization of interatomic interaction. Students can investigate the interatomic force as a function of the distance between two atoms. They will find that when the atoms start to overlap, they do not get closer no matter how hard the student pushes the spring, and the attraction force is the greatest at a certain distance but quickly diminishes when the atoms are further apart. In this way, students will discover the van der Waals force. This activity can be extended to teach other atomic-scale interactions, such as ionic bonds, covalent bonds, hydrogen bonds and protein-ligand docking.

Collaborating on inquiry

Mixed-reality labs can use multiple sensors to activate and enhance multimodal perception in science simulations. This allows a group of students to manipulate a simulation jointly using multiple inputs. For example, one student exerts force to compress or decompress a virtual gas while another uses a hot or cold object to change its temperature. Together, they investigate Gay-Lussac's law (the pressure of a gas is proportional to its temperature). Or imagine two students each controlling the temperature or number of molecules of a virtual gas in a compartment separated from the other by a piston. They would discover Charles's law (the volume of a gas is proportional to its temperature) or Avogadro's law (the volume of a gas is proportional to its molecule count). This kind of mixed reality enables students to physically play the roles of different science concepts and learn their relationships collaboratively.

Next-generation educational technology

The use of computer simulations across science is emphasized in the Next Generation Science Standards (NGSS). Uniting student actions in the real world with the reactions of simulated molecules, mixed reality provides an unprecedented way to interact with science simulations. It represents an important direction of next-generation educational technology that promises to support NGSS.

LINKS

Mixed-Reality Labs
http://mrl.concord.org

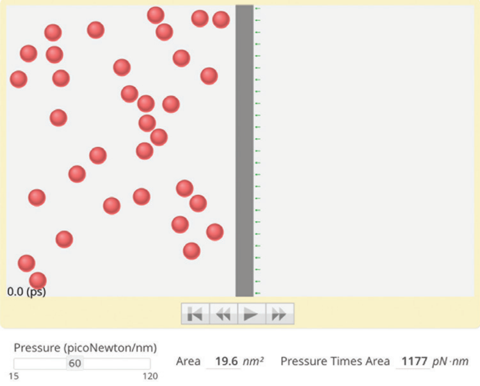
Under the Hood:

Inputs and Outputs to Next-Generation MW Interactives

Richard Klancer
(rklancer@concord.org)
is a developer.

By Richard Klancer

Our Next-Generation Molecular Workbench (MW) allows you to build Web-based simulations to explore emergent scientific phenomena. Years of experience tell us that learning happens best when students actively manipulate such models to ask and answer questions—and the Next Generation Science Standards call for students to do just that. Next-Generation MW helps foster inquiry with models by supporting custom properties, which you can define to expose the most relevant features of the model to observation and direct manipulation.



Area versus pressure interactive. Adjusting the slider changes the leftward force on the dark gray "piston."

By embedding a snippet of JavaScript code into the definition of a Next-Generation MW interactive, you can create an *output* property whose value at any time is a function of the current state of the model in the interactive. Similarly, you can define a *parameter,* which, when changed, runs a script to match the state of the model to its value. Either type of property can be graphed against time or bound to on-screen controls. Moreover, graphs and controls "just work" when a property changes, for example, when a user adds cold atoms to a box, instantaneously changing an output that reports the average speed of atoms in the box, or when a user revisits a past state of the model, which had a different value of some parameter. This encourages systematic exploration because students' manipulations are representable, recordable and reversible.

Consider a 2D simulation of nonreactive noble gas atoms compressed into the left side of a box at constant temperature by a piston. (See an example at http://mw.concord.org/nextgen/area-versus-applied-pressure.) The core Next-Generation MW engine, called MD2D for Molecular Dynamics 2D, understands the simulation as a set of atoms, an obstacle (perfectly hard rectilinear object of fixed shape and density), and so on.

Suppose we want students to explore the "volume" of the gas (or, rather, the area, since we're working in two dimensions) versus pressure applied. MD2D does not know that the obstacle is a piston, nor that we care about the force on it divided by its height. Therefore, we add an item named "pressure" to the parameters section of the JSON describing an interactive, having as its `onChange` property this JavaScript code:

onChange property

```
var pressure = value,
    length   = getObstacleProperties(0).height,
    force    = -1 * pressure * length,
    mass     = getObstacleProperties(0).mass;
force *= 6.022e-7; // Converts pN to MW's force unit, amu*nm/fs^2
setObstacleProperties(0, { externalAx: force / mass });
```

The parameters entry tells MD2D to add pressure to the list of properties it "knows" about, and the `onChange` code describes how to update the force applied to the piston when requested pressure changes. The pressure parameter can be bound to a UI control (as in the demo) and is recorded, so that when you step back in the model's "tape recorder" you see the parameter value that prevailed at that time.

Because we save complete state, even conceptually irreversible `onChange` actions can be reversed: changing the "number" parameter in the interactive at http://mw.concord.org/nextgen/area-versus-number destroys or creates atoms, but you can always rewind the model to any point in its history and restart it from there. Inherent reversibility frees students to investigate without having to worry about messing up the simulation, making them free to explore.

LINKS

Next-Generation Molecular Workbench
http://mw.concord.org/nextgen

Innovator Interview:

Sam Fentress

(sfentress@concord.org)

Q. Tell us about your background.

A. I was born in Rome to American parents and grew up there. I attended an English international school based on the British A-level system and came to the States to study liberal arts at Wesleyan, where I created my own major in cognitive science.

I did a Master's in Artificial Intelligence in Edinburgh and worked on a genetic algorithm using a theory of evolution that hadn't been applied before. It was based on Gould's theories of "exaptation"—a mechanism by which traits that were evolved for one purpose could be co-opted for another use. I was able to apply this to several known hard problems in evolutionary algorithm, with very good results. One of the exciting things about that has been seeing a sudden slew of articles in computer science journals in the past few years using this technique and citing my work.

I then found myself in Cambridge [MA], working at a language lab as a research assistant. I wrote a new, open-source Java program to present the language tests. Other people have continued to make improvements to it, which is great.

Q. Do you go back to Italy frequently?

A. My parents are still in Italy, and my family gets together in Tuscany most summers. We spend the morning deciding what to have for lunch, making it, then eating for three hours. We spend the afternoon deciding what to have for dinner, which lasts until midnight. A lot of wine is drunk.

Q. Did you travel when you were growing up?

A. We went everywhere—throughout the Mediterranean, North Africa, Eastern Europe. I worked on an archeological dig in Tunisia with my mother for several summers, which was fun. We found Roman cities centered on the production of murex, a seashell that you can crush to create purple dye for togas.

Q. How did you learn about the Concord Consortium?

A. The Concord Consortium was the only place creating interesting, open-source models and teaching interesting science. It is mission driven. Everyone is interested in helping students visualize science in ways they haven't before. I think a programmer is happier if they believe in what they're coding.

Q. What are some interesting things you've worked on?

A. I've worked on three evolution or genetics programs, two with dragons, which is great because I get to tell people I'm working with fire-breathing dragons. I also work on a project for teaching electronics, and can see the SPARKS product being widely disseminated because it's a nice, simple program to teach quite complicated concepts. And I've been working on Next-Generation Molecular Workbench, which has been engaging because I've had to learn new physics to program it.

Q. Why open source?

A. It's fun to discover a great library and to collaborate on code, working to create something cool and useful. We've had experiences of people making comments on our code and submitting patches without being asked. We try to give back and submit patches, too. That dialogue between developers pushes us all to make better stuff.

Q. What do you like to do outside of work?

A. Coding all day makes me want to build with my hands. I've tinkered with Arduinos and designed simple toys. I've also spent time at Artisan's Asylum, a local makerspace, welding and making wooden furniture. And I probably spend an hour or two cooking every night.

The Concord Consortium

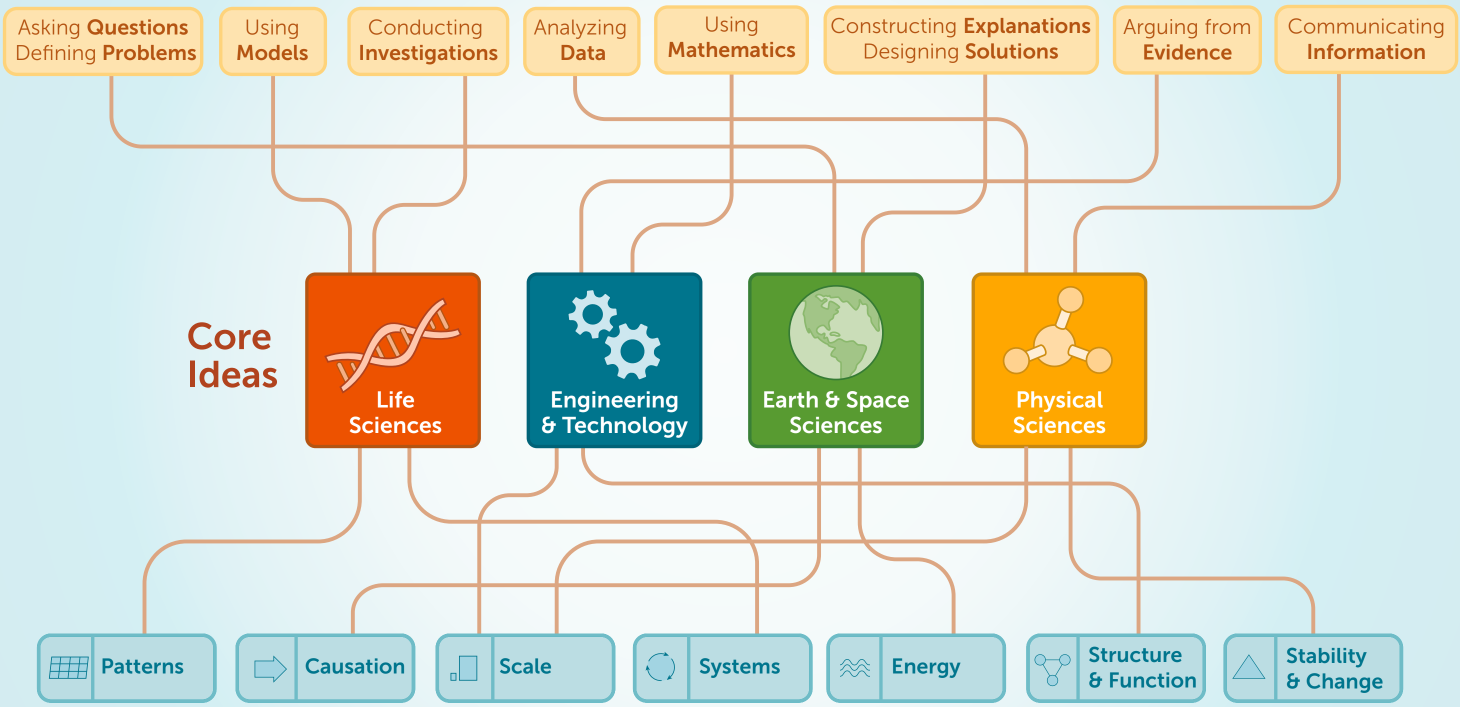
25 Love Lane, Concord, MA 01742

Find your path through the **NGSS**

Find your path through the Next Generation Science Standards with help from the Concord Consortium. Throughout this issue of *@Concord,* we describe multiple paths through the new standards and highlight the many ways technology can enhance these paths.

Discover a new approach to teaching with the NGSS.

1. Start in the center with a core idea. What do you teach?
2. Add a scientific and engineering practice—or two!
3. Add a crosscutting concept.
4. You've created one path through the NGSS. Learn how Concord Consortium resources can help you find more paths on pages 8-9.



Practices

Asking **Questions** Defining **Problems**
Using **Models**
Conducting **Investigations**
Analyzing **Data**
Using **Mathematics**
Constructing **Explanations** Designing **Solutions**
Arguing from **Evidence**
Communicating **Information**

Core Ideas

Life Sciences
Engineering & Technology
Earth & Space Sciences
Physical Sciences

Patterns
Causation
Scale
Systems
Energy
Structure & Function
Stability & Change

Crosscutting Concepts

See our interactive version at **concord.org/ngss**

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