

REALIZING THE EDUCATIONAL PROMISE OF TECHNOLOGY

Why Are Progressions Important?

A sequence of model-based activities supports student understanding.

BY BORIS BERENFELD AND
ROBERT TINKER

There is a disturbing tendency to treat educational materials as building blocks that can be assembled in any convenient order. “Knowledge engineers” think they can start with “learning objects” that can be automatically assembled into meaningful instruction.

Such designs ignore the central role of sequences of content and the importance of the progressive integration of ideas that creates knowledge and expertise. Core content needs to be returned to again and again, with each encounter deepening student understanding and increasing the web of associations that is a critical attribute of true knowledge.

At each step, a curriculum designer must

consider what the student already knows, what misconceptions are likely, what can be learned now, and what is important for subsequent steps. This need not preclude inquiry, but is required to make learning of key ideas and processes successful.

Creating a coherent progression in science areas that are changing is particularly challenging. For instance, advances in molecular science in general and in molecular biology in particular are happening so rapidly that simply memorizing the tenets of yesterday no longer ensures true fluency in the field. Even biology’s vaunted Central Dogma (DNA codes RNA, which codes proteins)—a cross between classical genetics and modern molecular science—is showing cracks. To truly understand new advances in molecular biology, students need molecular literacy that includes understanding the molecular concepts underlying the constructs of modern biology and the ability to apply these concepts

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STEM Education Needs a Major Overhaul

BY ROBERT TINKER

Science education could be so much better if only we implemented it based on what we know about teaching and learning. Decades of research, pilot studies, and innovations have conclusively demonstrated how science education could be improved. We should also include changes in the disciplines and newly discovered science content, and most importantly, we should exploit the many opportunities that technology provides to fundamentally change what is taught and how students learn. These changes could result in huge advances in student understanding.

There is wide agreement that something should be done about science, mathematics, and engineering education. Increasingly, industry

is high-tech, jobs demand technological savvy, civic decisions are based on mod-

els and statistics, and personal health requires medical expertise. Societies that implement a 21st century science education will flourish while those that cling to antiquated models will be left behind. This was recognized recently in a flood of passionate and reasoned calls for improvements in science education from business leaders, academia, futurists, commentators, and even the military. Clarity about what to do, however, has been lacking. Most plans involve some combination of higher standards, harder tests, more required courses, more AP courses, better teachers, higher pay, or smaller schools. These changes simply result in more of the same old instructional practices. They fail to support needed change in what is taught, how it is taught, and how it is assessed.

A new, comprehensive and coherent curriculum is needed from kindergarten through the first years of college in all STEM subjects (science, technology, engineering, and mathematics) that focuses on fewer and deeper concepts taught conceptually, coherently, and in meaningful contexts. These core concepts can provide touchstones around which a profusion of math, science, and engineering topics can be organized in a far more interdisciplinary way

A good place to start a reform effort is the *secondary* STEM curriculum. Success at the secondary level would have a profound effect on both elementary and college education. Such a radical

design for STEM education reform must be based on the following principles:

- **Research Based.** There is a growing consensus on how to teach STEM subjects. Students need to be actively engaged in thinking critically about key topics, so that they examine their own ideas and build associations.
- **Unified.** Mathematics, engineering, and the sciences should be linked as much as possible. An integrated math-science sequence should take advantage of a spiral curriculum. Technology and engineering, usually orphaned, should be woven throughout these courses.
- **Conceptual.** There should be far less emphasis on facts and algorithms, and far more on core concepts. For instance, the calculus concepts of derivatives and integrals would be covered in science and engineering contexts without focusing on their proofs or calculation.
- **Technology Enhanced.** A reformed STEM education would exploit many advantages of current technology for experimentation, modeling, collaboration, and resource acquisition.
- **Standards Compliant.** STEM reform can adhere to the national standards and go far beyond them in many cases by emphasizing fundamental concepts and featuring an emphasis on inquiry, applied math, and engineering found in the standards.
- **Teacher Friendly.** Teachers should have extensive support for teaching the new content and adopting new instructional techniques. The technology should give teachers detailed and timely feedback about student learning so they can adjust instruction.

This vision will be difficult to achieve. Few schools have the resources and flexibility to implement these recommendations. Not all the needed curriculum pieces currently exist, and few have been subjected to classroom testing. And teachers will be required to learn new content and better instructional strategies. Still, this vision cannot be dismissed simply because of the challenges to its implementation. We hope adventurous educators, schools, and institutions can agree on an agenda for comprehensive reform of STEM education, along these lines.

Robert Tinker (bob@concord.org) is President of the Concord Consortium.

A new curriculum is needed that focuses on **fewer and deeper concepts.**

How Can Assessment Be Improved?

Digital Performance Assessment May Be the Answer

BY PAUL HORWITZ

Assume that you are selecting items for an assessment leading to certification of electronic technicians. Which of these would you choose?

- Define the term “digital multimeter” and give two examples of its use.
- An RC circuit consists of a 100-ohm resistor in series with a 10-microfarad capacitor. What is its time constant?
- Using a function generator and an oscilloscope, find out what is wrong with this power supply and fix it.

It’s a trick question, of course. The first of these assessment items stresses irrelevant language skills and the second involves plugging numbers into a memorized equation. The third clearly comes closest to simulating the conditions a technician might actually encounter on the job. Nevertheless, the questions on certification exams for electronic technicians are far more likely to resemble the first two items than the third. The reason is simple: “performance assessments” like item three are much more costly to administer and score.

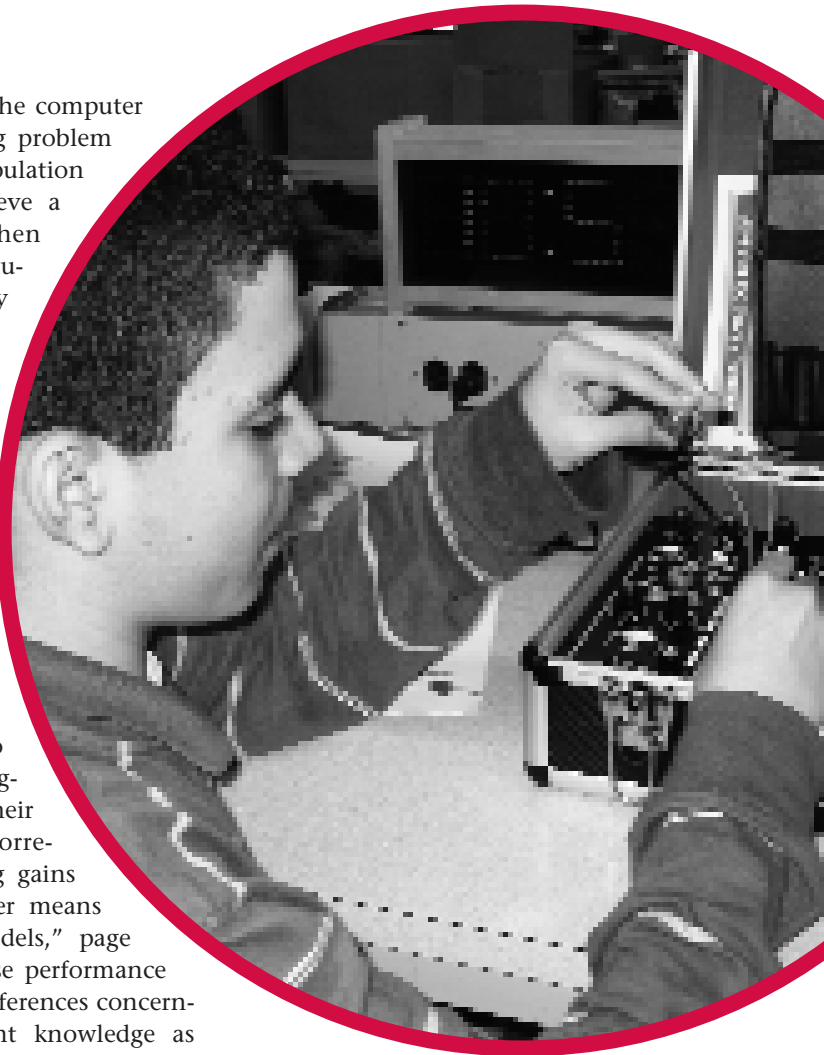
Or are they?

Computers can simulate any electronic circuit or measuring device; moreover, they can monitor and report on the actions of their users. All that’s missing, then, is the ability to analyze those actions and make valid inferences from them concerning a student’s knowledge, understanding, and skill, and her ability to combine those assets to solve realistic problems.

For several years, the Concord Consortium has been experimenting with computer-based models of real-

world phenomena. The computer sets up a challenging problem that involves manipulation of a model to achieve a specific goal. It then monitors what the student does, possibly offering hints or asking questions at critical junctures. Most important, the computer logs the student’s actions—answers to questions as well as experimentation with the model. By aggregating such data from thousands of students, we have been able to detect statistically significant patterns in their performance that correlate to their learning gains as measured by other means (see “Interactive Models,” page 12). Thus, we can use performance data to make valid inferences concerning students’ content knowledge as well as their ability to explore and reason with models.

To date, our work with these models has involved science students, not budding technicians, but that’s about to change. With support from the National Science Foundation’s Advanced Technological Education Program, we are adapting our technology to assess students as they troubleshoot computer models of faulty electronic circuits, using models of standard measuring equipment. This will enable us to pose challenges similar to the one described above, and to monitor, for instance, whether the student knows where to place the probes of the oscilloscope and how to set its time scale.



We have developed the technology necessary to give teachers those tools, but so far we have concentrated our data reporting tools on the needs of researchers, not teachers. The challenge now is to adapt our technology to create formative assessments that can identify the struggling students and describe their difficulties in enough detail so the teacher can help them, long before they are confronted by that high-stakes, multiple-choice certification exam.

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to various biological phenomena.

Yet literacy in any field, particularly in molecular science, cannot be taught by treating curriculum components as building blocks assembled in any order. Proper sequencing that guides students to construct a rich molecular worldview useful for explaining a wide range of phenomena is critical.

Students Need More than “The Chemistry of Life”

In the traditional biology curriculum, molecular science is presented in a fragmented way, highlighting limited concepts. Most, if not all, ninth grade biology textbooks include a section typically entitled “The Chemistry of Life.” Students are introduced to atoms, ions, and small molecules. This chapter traditionally includes a colorful picture of water molecules, with dotted lines between them referred to as hydrogen bonds. Another picture shows sodium and chloride ions attracted into a crystalline structure due to opposite charges carried by the ions, though this may create a misconception that attractions exist only between ions. There is nothing or very little about polarity or van der Waals forces.

In the “Chemistry of Life” chapter, macromolecules come next. Here car-

bohydrates, lipids, proteins, and nucleic acids are introduced. Students memorize the four nucleotides—A, C, G, and T—that make up DNA, look up the chemical formulas of 20 amino acids capable of combining into polypeptide chains, and learn that proteins have primary, secondary, tertiary, and quaternary structures.

To address the genetic code, such a chapter has a table linking 64 possible triplets of nucleotides to 20 amino acids. As the finale, it mentions that when DNA code is translated into proteins, the proteins determine traits. Since Mendelian genetics usually comes much later in the course, students cannot question at this point how traits are linked with proteins. A couple of months later, by the time they study Mendel’s Laws, “The Chemistry of Life” looks like a distant and disconnected mirage.

While this approach refers to atomic-scale interactions, it doesn’t develop the connections necessary to build a strong understanding or reasoning skill at the molecular level. Because many critical molecular principles underlying these ideas had been considered hard to teach, they were often skipped, lightly touched upon, or taught quantitatively through mathematics. But unless students were mathematically literate, this was not an effective approach.

Stepping Stones to Molecular Literacy

With the support of the National Science Foundation, we have developed a sequence of model-based activities to support student understanding of key concepts that underpin modern biology. *The Stepping Stones to Molecular Literacy* helps students reason about microscopic and macroscopic phenomena using what they learn about atoms, molecules and their interactions, and the resulting emergent phenomena. The specific sequence is critical because each activity builds upon the ones before it. Like Russian nesting dolls, each activity encompasses the prior ones, thus building a progression of molecular understanding.

The following is an example of a model-based progression of activities. (For the complete list of *The Stepping Stones to Molecular Literacy* activities see: <http://molo.concord.org/database/browse/stepping-stones/>)

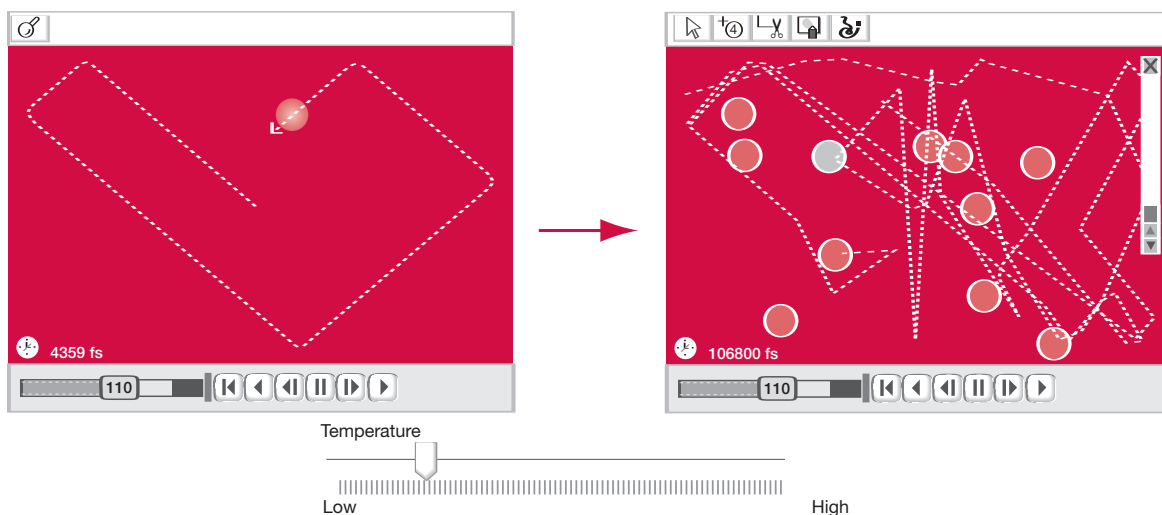
1. Atomic Movement Never Stops. Students start with a single molecule in a virtual container and gradually add molecules to the system. As they add heat energy, they observe increased frequency of molecular collisions. Students can select a single molecule and trace its path to see how its motion is affected by collisions with other mol-

Transcribe Translate Stop the Model Reset the Model

or

Transcribe step by step Translate step by step

Using the DNA to Protein model, students can compose any sequence of nucleotides, transcribe it into mRNA, and then translate that into a small protein. They can then view the protein folding in water or oil. This is how nature makes a 3D protein from a one-dimensional DNA sequence. Experimenting with such a model allows students to explore the relationship between a DNA sequence and the resulting protein structure, arguably the most important concept in molecular biology.



In the Brownian Motion activity, students observe the motion of a single particle, and then increase the number of particles in the model, as well as the amount of heat energy. They follow the motion of particles as they collide and discover the cause for their apparent random motion.

ecules. By changing the amount of heat in the system, students can address issues of thermal motion, average kinetic energy of molecules, and temperature. This dynamic picture of matter composed of constantly moving and colliding molecules must be a foundation of students' mental models.

2. It's a Sticky, Sticky Molecular World. Few students realize that *all atoms* attract one another. This fundamental idea is central to an understanding of the atomic scale. It is quite common for students to think that only opposite charged ions are attracted to each other. Our model allows them to experiment with systems that depict attractive forces, such as van der Waals and hydrogen bonds that exist between atoms and molecules.

3. Relating to Water: Hydrophilia and Hydrophobia. The earlier models of random thermal motion and the attraction and repulsion between atoms and molecules are now applied to understanding the unique properties of water and aquatic solutions. Students simulate the attractive forces between water molecules called hydrogen bonds, experiment with adding ionic and non-ionic compounds, and

observe the interactions between water molecules and the solute.

4. Protein Chains and Water. With the above knowledge, students investigate how a protein chain made of a combination of hydrophobic and hydrophilic amino acids behaves in water and lipids (the cell's environment). Students see how hydrophilic amino acids pull the chain toward water and how the hydrophobic amino acids are excluded by water and thus move inside the chain. Students learn how these processes shape the protein.

5. Genetic Code and Proteins. Students are ready to embark on experiments based on the Central Dogma. Using a model that contains a DNA coder and is capable of generating proteins according to the genetic code, students can create any sequence of nucleotides, launch protein synthesis, and observe the resulting composition of the chain of amino acids; they also can predict and observe the resulting shapes of the polypeptide chain in water, and develop a conceptual understanding of the genetic code and its connection with the shapes of the resulting proteins.

6. Molecular Self-Assembly. When students explore the folding of the polypeptide chain into a specific three-dimensional shape, and the assembly of proteins in a complex quaternary structure, they use fundamental ideas of physics and chemistry, including the idea that kinetic motion brings the pieces in contact and the charge and

shape knits units together, creating shapes with biological consequences.

7. Mutations and Illness. If one truly understands the concepts leading to the Central Dogma, one should be able to reason about the molecular nature of mutations. To grasp the concept of mutations, students are able to alter the genetic code and compare how deletions, insertions, or substitutions of the coding sequences affect the amino acid composition and the shape of the protein. This molecular hands-on learning allows students to tackle the cause of a genetic disease, such as sickle cell anemia.

Thus, from simple concepts of random motion and the stickiness between particles, a sophisticated view of the molecular world emerges. Generations of biology teachers used their eloquence and tons of chalk to convey these ideas. For our students, modeling and visualizing the processes of molecular interactions are only a click away. *The Stepping Stones to Molecular Literacy* builds a unique progression of understanding. Armed with this foundational understanding, students can take on more complex explorations, all the way to the Central Dogma, and further, to new discoveries in molecular biology.

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LINKS Progressions



The Stepping Stones to Molecular Literacy

<http://molo.concord.org/database/browse/stepping-stones/>

What is 21st Century Secondary Engineering?

BY BRADLEY HEILMAN

Increasingly in society, much of what surrounds us has been engineered. We wear clothing designed to wick moisture from the body, stretch, stay wrinkle free, and protect us from UV radiation and insects. We live in structurally sound buildings with optimized lighting, heating and cooling, smoke detection, and numerous other technologies. We use cellular phones that know the correct time in every zone, can download digital media, and run on a rechargeable battery for several days. But how does all this work?

Relative to its importance, engineering is greatly underrepresented in elementary and secondary education. As a consequence, many high school students are unaware of engineering-related careers and unable to make the informed civic decisions demanded of citizens in a technological society.

In this era of teaching to standards, it is important to note that national standards have clearly defined the skills and knowledge expected of secondary students in engineering and technology. Engineering is treated extensively in the *National Science Education Standards* and the *International Technology Education Society*. The boldest statement about secondary engineering is found in the *AAAS Benchmarks*, in which two of the twelve describe engineering topics: Benchmark 3, “The Nature of Technology” and Benchmark 8, “The Designed World.”

To illustrate the detail and specificity of these benchmarks, consider just one in the “Energy Sources and Use” sub-section of Benchmark 8 for middle grades: “Students should know that...electrical energy can be produced from a variety of energy sources and can be transformed into almost any other form of energy. Moreover, electricity is used to distribute energy quickly and conveniently to distant

locations.” This example shows the close association between science and engineering and suggests that the 21st century curriculum should integrate engineering topics with science instruction. The following section describes how this can be done.

Projects in Science, Math, and Engineering

Easy access to information and computer technologies (ICT) can revolutionize secondary engineering education. Of course, ICT can be studied as an important engineering topic—students can learn about the computer, programming, interfacing, and networking. But just as importantly, ICT can facilitate learning all engineering topics, in the way that ICT supports major innovations in math and science education, as described throughout this newsletter.

The two uses of ICT are mutually reinforcing: students who learn about ICT technologies are also empowered to use these technologies to expand their math and science learning. And the ability to make one’s own technologies gives students insights into otherwise “black boxes,” expands the range of possible investigations, and reduces equipment costs.

Student projects are the proven strategy for engineering education. This approach provides a hands-on

learning experience, where students get a genuine opportunity to be inquisitive and come up with solutions. Projects are best undertaken in small teams with defined roles, much the way most science and engineering is done. The potential pitfall in the use of projects is that they can be too open-ended, and consume time and resources. To avoid getting mired in low-yield projects, the curriculum needs to focus on well-defined activities that provide guidance and have clear educational purposes. This can be done with highly interactive computer-based activities that provide motivation, opportunities for reflection, guidance, hints, and support for sharing reports.

The following two projects illustrate the power of projects and the role of ICT technologies.

Taking Measurements: Natural Frequency and Resonance

Did you know that the human stomach resonates at a frequency of 4-8 Hz (cycles per second), and that your head resonates around 20-30 Hz? Fortunately, the engineers designing cars are aware of this (or you might get car sick if the car’s vibrations occurred at the same frequency as your head or stomach). The topic of natural frequency can be investigated using a two-dollar microphone connected to a computer,

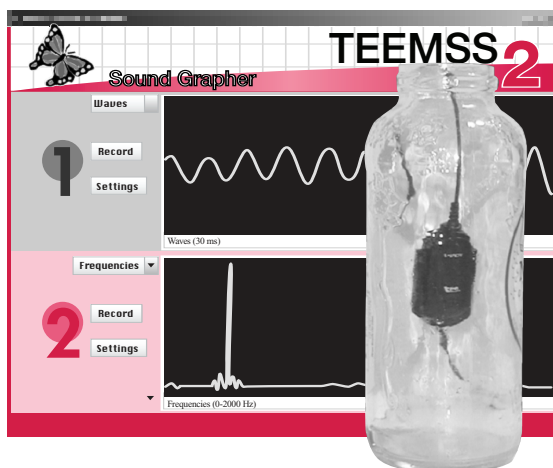


Figure 1. The natural frequency of a glass bottle can be measured with a \$2 sensor and a computer. The top graph shows the waveform of the natural frequency within the bottle. The bottom graph shows the frequencies present at resonance.

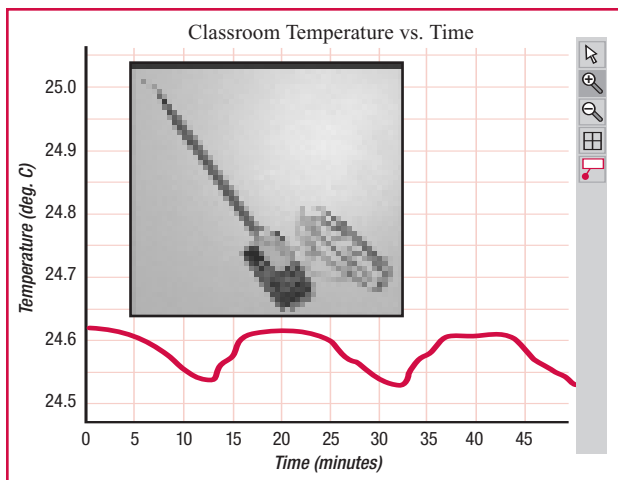


Figure 2. A graph showing temperature in a room heated under thermostat control. The fluctuations are typical of a system with feedback. This can be measured with a student-built temperature sensor (inset).

a glass bottle, and free software developed by the Concord Consortium called the Sound Grapher (see @Concord, Fall 2005). Figure 1 shows the natural frequency of the bottle, as depicted by the Sound Grapher. Using free tone generation software from the Web or installed on your computer, this activity teaches the fundamentals of resonance and tuning, and can be extended to investigate mechanical principles in construction, car and instrument design, and electrical principles in circuit or cell phone design.

Understanding Systems: The Classroom Thermostat

Is the air temperature in your classroom constant? Inside air temperatures are always changing as air is heated or cooled by objects within the classroom, air mixes from sources such as windows and doors, and other factors. Figure 2 shows a student-made fast-response temperature sensor, which costs under \$10 in parts. This sensor can quickly measure small changes in air temperature. The graph shows the fluctuations caused by a room air heating system. The air temperature gradually drops, the heating system turns on, the temperature rises, and the system turns off. Students can measure these changes, then build their own heating system using a temperature sensor and a switch-operated heating element or fan. This feedback loop is part of every heating and cooling system. Such feedback loops are all around us, from nightlights to the radiator fan in a car.

Core Concepts

The 21st century secondary engineering curriculum should be built around a carefully designed progression of projects such as these. The projects would increase in sophistication throughout the grade levels and be selected to focus on core engineering concepts:

- *Hands-on design and construction of both mechanical and electrical systems.* Students need to develop a range of technical skills and common construction sense. They should learn about materials, time and financial constraints, and flexibility and compromise in project planning and execution.
- *Taking measurements and testing designs.* Some measurements may be done with mechanical tools (e.g., a ruler), but often the best approach is to use sensors and computers. Thermistors, phototransistors, Hall effect probes, and other inexpensive sensors can interface to a computer with a general-purpose voltage input. This do-it-yourself approach greatly expands the range of applications of probeware while also introducing students to the rudiments of electronics and interfacing.

- *Using mathematical models and simulations.* Students can extend their understanding and investigate situations not easily explored through other means. Models also introduce students to a widely used engineering tool. Almost every large-scale engineering project is modeled prior to production, which helps determine feasibility, safety levels, and costs of construction and operation.
- *Understanding engineering systems.* Systems are collections of components that work together to achieve a result. A system can be compact—such as the components in a pair of pliers or a mechanical clock—or as complex and widespread as the phone system. Students aware of the bigger picture—the components, the interactions between components, and the overall goal—are equipped for innovating or managing better solutions.

Conclusion

Engineering and technology are continually advancing in our society. Such advances are a call for more attention to 21st century secondary engineering. They are also an indispensable enabler: as computer technologies become more prevalent, they can be leveraged to teach concepts of engineering in a meaningful, effective, project-based curriculum. This type of curriculum necessitates an understanding of science and math as building blocks for engineering.

The Concord Consortium is taking a first step at developing aspects of such a curriculum, funded by the NSF under an ITEST (Information Technology Experiences for Students and Teachers) grant. Teachers nationwide will help us use both computational models and real-time data acquisition to create activities appropriate for their classrooms and their communities. These activities will merge engineering with science and math, to the benefit of all STEM subjects, and more importantly, the benefit of the 21st century student.

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LINKS 21st Century Secondary Engineering



National Science Education Standards

<http://www.nap.edu/readingroom/books/nses>



International Technology Education Society

<http://www.iteaconnect.org/TAA/PDFs/xstnd.pdf>



AAAS Benchmarks

<http://www.project2061.org/publications/bsl/online/bolintro.htm>

What Flows When Heat Flow

ROBERT TINKER

Heat energy is hard to understand. You cannot see it, you cannot measure it directly, and it is not a material. In fact, you can only infer heat energy indirectly from its ability to heat or cool things. No wonder everyone—including the eminent scientists Lavoisier and Laplace—had it so wrong for so long. They thought that something called “phlogiston” flowed like a gas from hot substances where it was dense, to cold ones where it was less dense.¹

But no one ever found phlogiston. Scientists concluded that if it existed, it had no mass, or maybe a negative mass. They got it confused with fire, oxidation, and other sources of heat. It’s no wonder students have problems understanding heat. The following lesson can help your students to unlock the mystery.

Overview

This computer-based lesson uses the Molecular Workbench (MW) software to make heat visible and to provide a playground where students can interact with heat and temperature, pose questions, run experiments, and see what happens. MW is a computational model that simulates how atoms and molecules interact. Understanding atomic interactions is essential

for understanding heat flow, so experimentation with MW gives students a unique way to figure out what’s happening on their own.

Kinetic energy is made visible in MW by coloring atoms. When still, atoms are white, but as they speed up, they become pink and then red.

Students learn that kinetic energy is associated with speed and that it can be transferred through collisions. From there, it’s a short step to see that



Figure 2. Newton's Cradle.

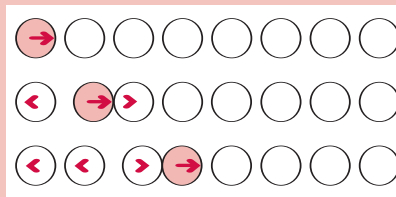


Figure 3. A series of snapshots of the MW simulation of Newton's Cradle.

atoms will share some of their kinetic energy with any other atoms they contact and that the average kinetic energy is temperature.

Step One: Why Are Those Atoms Red?

Go to the Molecular Workbench database of activities at: <http://molo.concord.org/>

Jump to Activity #292, “What is Heat Flow?”

This activity consists of a series of pages, each containing a model. On the first page is an activity (see Figure 1) designed to familiarize students with the Molecular Workbench software, and the association between kinetic energy and the color of the atom. Using the keyboard’s arrow keys to apply force, the user can “steer” an atom. One warm-up challenge consists of turning the white atom red and then white again as fast as possible.

Note

- 1 For more information, see http://en.wikipedia.org/wiki/Caloric_theory

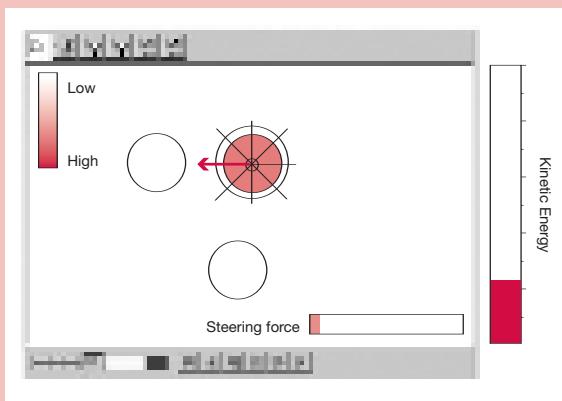


Figure 1. This model starts with three atoms at rest. The student can steer the one atom with arrow keys. As it speeds up, it turns red. The challenge is to get the steered atom white and the other atoms red.

Step Two: Newton's Cradle

This model mimics that familiar pendulum toy called the Newton's Cradle (Figure 2). Four atoms in a row are hit by another atom. All the atoms are red if they have kinetic energy. The model—like the desktop toy—dramatically illustrates how kinetic energy moves from one atom to the next, down the line to quite distant atoms (Figure 3).

In real substances, of course, atoms are not in perfect lines, so the energy does not flow quite so rapidly, but the idea is the same.

Step Three: Heating by Hitting

In this step, students are challenged to give kinetic energy to the last atom on the lower left (Figure 4), starting with everything at rest. This is an important step—and a natural progression from Newton's Cradle—because it introduces a solid crystal and shows that kinetic energy can spread among its atoms.

The obvious way to achieve the goal is to steer the big atom to the right at maximum speed. After two hits, the nearby atoms have a lot of kinetic energy, and the kinetic energy begins to spread down throughout the solid. As you run the MW model, you can see the red atoms ripple

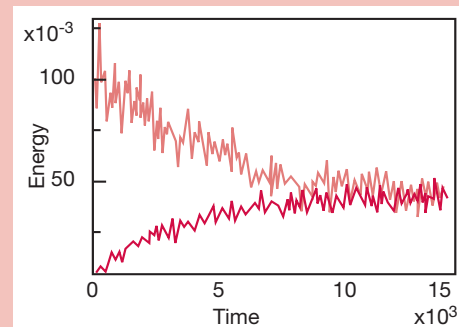
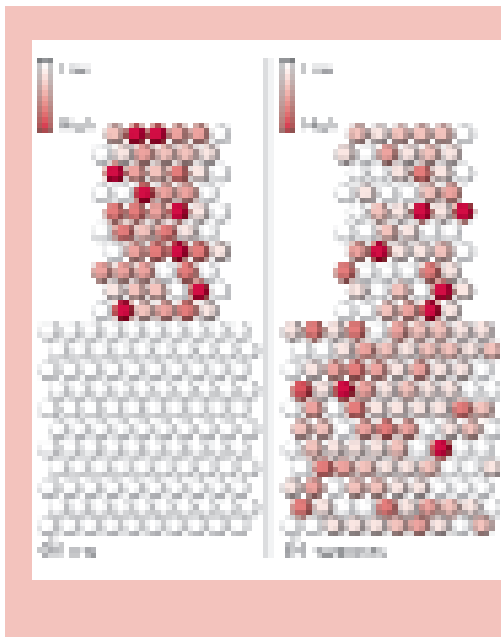


Figure 5. A solid with a lot of kinetic energy is placed on top of one in which the atoms are at rest. The left illustration shows the starting point. The right shows what happens after a short time has elapsed. The graph, which is generated in real time during the simulation, shows that the average kinetic energy of the two kinds of atoms converge to a single value.

outward from the point of impact. Ask your students to explain in detail why the red color seems to hop from one atom to another at random.

Step Four: Heat Flow Experiments

Students are now prepared to understand energy flow from one object to another. The final step uses a model of two substances, one with lots of kinetic energy and one with none. The model has the two in contact and gives the results shown in Figure 5. This might represent a hot cup placed on a counter. Have students experiment with ways to increase and decrease the rate of energy flow by

changing the starting positions of the atoms. Can the heat flow be stopped?

These experiments show that kinetic energy will transfer from atom to atom until all atoms have the same average kinetic energy. Since heat flows until temperatures are equalized, this justifies thinking of temperature as the average kinetic energy, and heat flow as the transfer of kinetic energy at the atomic level. This is a profound result with many implications in chemistry, biology, and technical fields.

Closing Thoughts

The Molecular Workbench allows students to explain and connect a wide range of concepts. In this short activity, students use guided inquiry to learn about kinetic energy and atomic collisions. They learn two foundational concepts: temperature is average kinetic energy and heat flow is simply the spread of kinetic energy. No equations or numbers are required; a purely conceptual approach can get the ideas across better than pages of equations and numbers.

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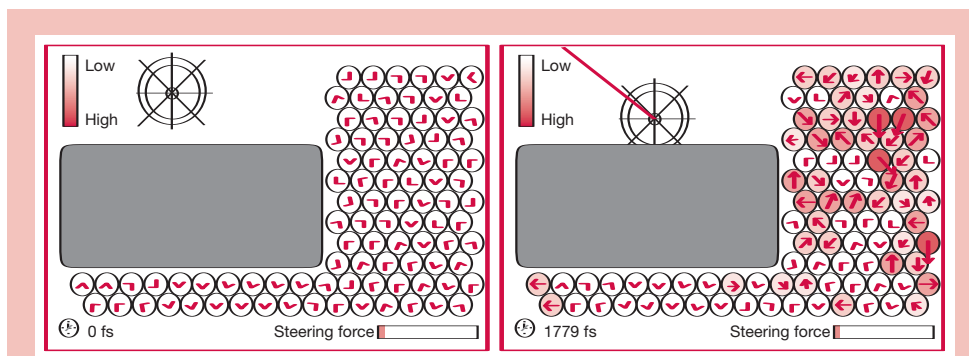


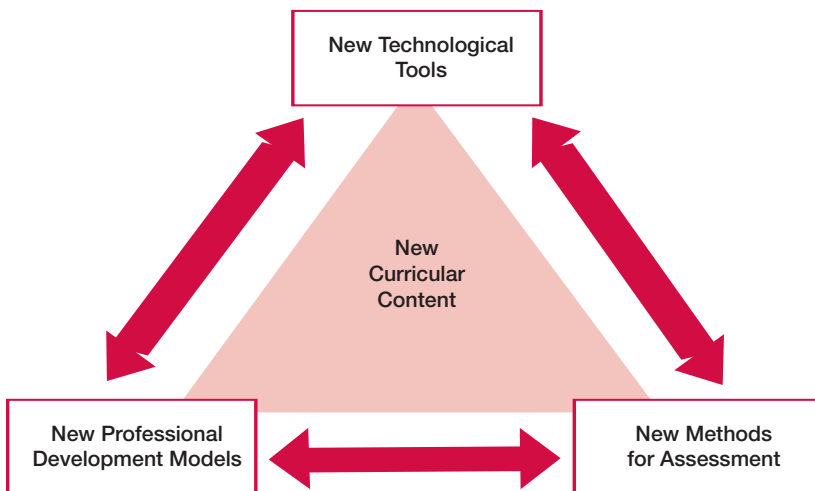
Figure 4. The starting condition (left) and after the big atom has hit the solid crystalline atoms twice (right). The atoms are held together by mutual attraction. The arrowheads in each atom indicate velocity. On the right, the leftmost atoms have been given some kinetic energy as indicated by the slight shading and their velocity vectors.

What is 21st Century Mathematics? Concepts, Not Computation

BY ROBERT TINKER AND GEORGE COLLISON

Twenty-first century secondary mathematics calls for a very different curriculum. The demands on workers and voters to make informed decisions require greater knowledge of concepts related to data, models, computers, and rates of change. But ubiquitous access to computers in schools, work, and home means that procedural and computational techniques are far less important, while learning more sophisticated mathematics concepts is possible. A transformation is required that results in greater emphasis on the many ways math helps us understand the world, and less on math for its own sake. We need to focus on concepts, not computation.

In the coming decade, developing and using real-world content will require new technology tools and new approaches to teaching and learning. It will also require new assessment methods and a commitment to teacher professional development.



New Content and Technology Tools

Educators must bring the ideas of mathematics to students so that they can recognize the power and potential of the deepest ideas of mathematics. New content includes a greater emphasis on a conceptual understanding of functional relationships, as in rates of change and accumulation. It also includes the use of modeling to develop and illustrate ideas. And it must demonstrate ways mathematics can support decision making, for

example, understanding graphs and percentages could help a voter interpret a political candidate's views on global warming or the budget deficit.

Over ten years of research by Jim Kaput and colleagues¹ with a large number of middle school and secondary students has shown that students can grasp and apply calculus concepts without first mastering formal notation. Using SimCalc software, students can create graphs of data obtained from a real motion detector or from simulations of the motion of an elevator, a car, or other object to explore the relationship between function and its derivative and integral.

Research has shown that using visualization tools such as TinkerPlots and Fathom, elementary through high school students can achieve sophisticated levels of statistical understanding. Computer-based models such as StarLogo, NetLogo, and AgentSheets are all environments in which students can create a set of rules (e.g., evolution, global climate change, phases of matter, or schools of fish) and watch for emergent behavior. This type of learning provides students with a broad conceptual understanding needed by everyone, not just those students planning a mathematics or technical career.

The *Seeing Math algebra interactives* developed by the Concord Consortium support an approach to algebra using the function concept as a central theme. With traditional approaches that offer exercises requiring manipulation of symbols and equation solving, teachers and students miss many opportunities to make connections to real-world, practical mathematics. The function concept unifies later study in algebra and the study of change in calculus; introducing functions earlier aids student understanding of mathematics significantly.

New Professional Development

In order to understand and use new content and new technology tools, mathematics teachers need a new type of professional development that mirrors the student experience by being grounded in student work as well as a cognitive theoretical framework.

Seeing Math online case studies² integrate videos of students at work, expert commentary on student thinking, online interactives that target key mathematical ideas, and threaded discussions. Within the course design, teacher participants watch online video clips of stu-

Notes

- 1 See <http://www.simcalc.umassd.edu/library.php>
- 2 Seeing Math courses are available at Teachscape and PBS TeacherLine.

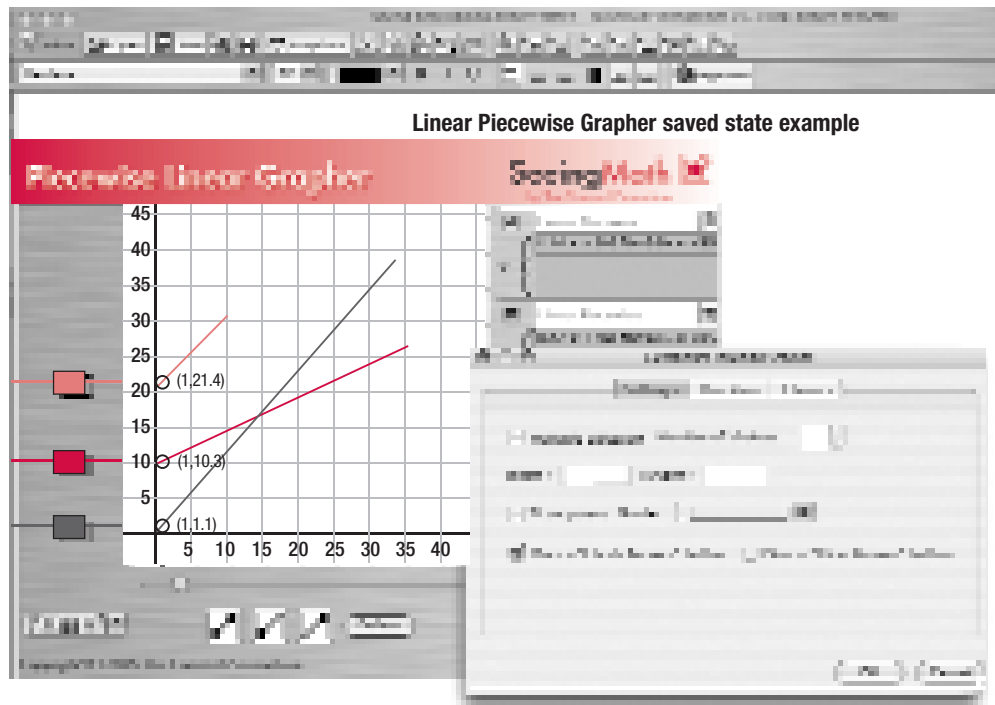
dents working through the same or similar activities to those the participants are working on. Participant collaboration and discussion of the activities helps illuminate key elements of mathematics and mathematics teaching. In contrast to older designs of online professional development in which an expert moderator acts as a “sage on the stage,” in Seeing Math courses expert knowledge is imparted in two ways: using videotaped expert commentary targeting specific ideas in the student work and participants’ experience gained by working through the activities themselves. As a result, participants make connections related to their own learning of mathematics as well as important new connections among graphic, symbolic, and dynamic representations that are critical in order to teach algebra effectively. The important aspects of mathematics they learn through these case studies are not accessible through traditional methods or refresher algebra or calculus courses.

Another powerful professional development tool developed at the Concord Consortium is the VideoPaper Builder™, which enables teachers or administrators to author their own web-based video cases. Just as students need to learn how to learn, teachers need to sustain their own professional development.

New Assessment Tools

Different forms of assessment must accompany these curricular and instructional innovations. The goal of the assessment should be to inform students and teachers about the level of understanding achieved, and of the next necessary steps in instruction. Large-scale standardized assessments provide information about an aggregate of student performances; they are of little use in addressing individual student needs. Extensive research by Paul Black at the Open University has shown that ongoing formative assessment that guides teaching and learning brings about increased learning as well as increased self-esteem for students.

The Concord Consortium’s MW Platform offers an example of a highly innovative design for ongoing formative assessment. MW Platform allows teachers to create their own stand-alone or web-based lessons using Seeing Math interactives, or other Java-based software.



The Seeing Math interactive “Piecwise Linear Grapher” in the MW Platform. This puts all instructions, challenges, help, and assessments in the same environment that can be easily edited and delivered to students.

The highly innovative report feature of the MW Platform enables students to create a series of annotated screenshots with explanations of their work. The MW report includes annotated graphs and student commentary that can be sent to the teacher or other participants. With MW, teachers can set up lessons using any of the above applets and customize activities and questions to suit their students’ local needs (for example, to change the context of the question or to meet specific local standards). The report feature enables students to capture dynamic “footprints” of their work and share them with other students and with a teacher for the purpose of formative assessment.

An Integrated Vision

This integration of new content, new tools, new professional development, and new methods of assessment is not just a dream realizable ten years down the road. The Concord Consortium has assembled and tested in classroom settings all of these components. Using software developed by the Concord Consortium and its collaborators, including an elegant case study professional development design and the formative assessment capacity of the MW Platform, high-quality mathematics will be accessible to all students.

LINKS 21st Century Math



Seeing Math algebra interactives
http://seeingmath.concord.org/sms_interactives.html

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Interactive Models: Helping Students Learn and Helping Teachers Understand Student Learning

BY PAUL HORWITZ, JANICE GOBERT, AND BARBARA BUCKLEY

If a picture is worth a thousand words, then for science learning an interactive model may well be worth a thousand pictures. Why are models such powerful learning tools? And what can we learn by observing how students experiment with them?

In October 2001, in partnership with Harvard University, Northwestern University, and Massachusetts public schools in Lowell and Fitchburg, the Concord Consortium launched *Modeling Across the Curriculum* (MAC), a groundbreaking, five-year research project. Since then we have developed dozens of model-based activities that cover such diverse topics as Newtonian mechanics, gas laws, atomic structure, and genetics. We have also built an extensive suite of tools for collecting

and analyzing the data generated as students use the models. Over the last three years approximately 400 schools in over 20 countries have registered with us and downloaded the MAC software. Each time students ran an activity, if they were online, we collected data—over 1.5 GB of log files. In all, over 18,000 students have contributed to our research in this way. As we wrap up the project this fall, our data analysis algorithms are converting those logs into useful information for researchers and teachers.

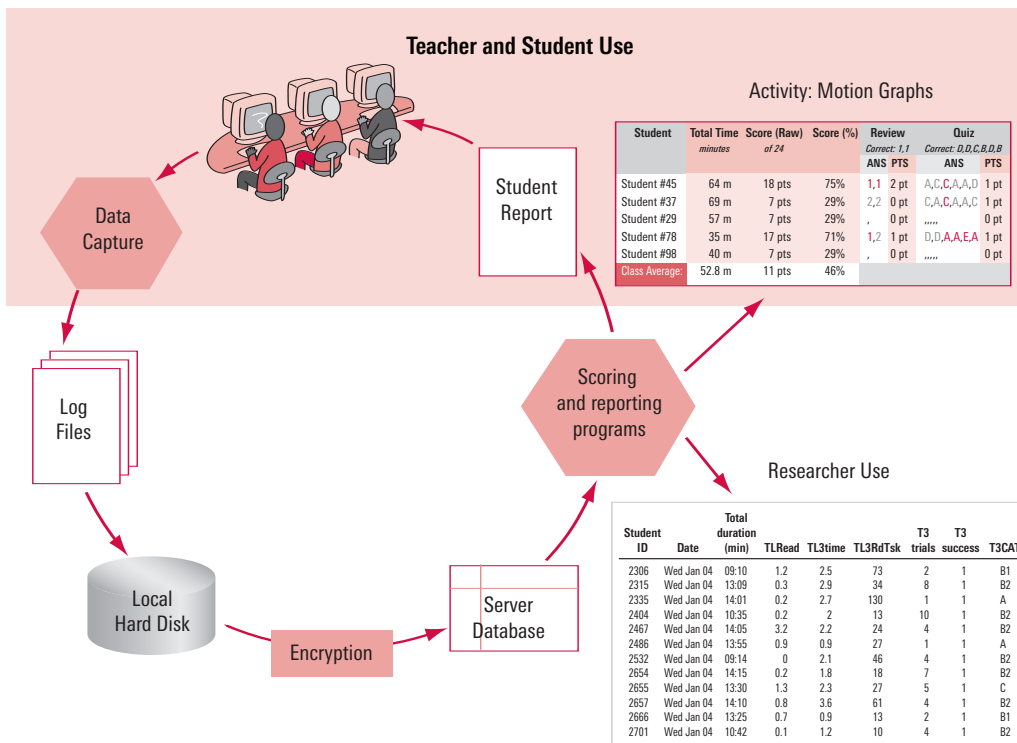
So what are we learning from all that data? First of all, students learned the science content from models. For instance, 98% of the physical science classes that used our Dynamica activities (which model Newtonian mechanics) showed significant learning gains on a post-test

to pre-test comparison. More important, the students who ran more models also learned more—in our genetics classes, the number of activities attempted by the students in a class accounted for 17% of the learning gains. That's not too surprising, but it's gratifying nonetheless—a “proof of principle,” if you will. But the really interesting part comes when you consider how the students used the models.

Actions Mirror Understanding: Performance Predicts Learning

Let's distinguish “process” data from “outcome” data. Outcome data describes what a student learns. It often appears in the form of answers to questions or solutions to numerical problems—whether presented as a post-test or embedded within an activity. Process data, on the other hand, describes how a student goes about solving a problem. For example, one of our genetics activities requires students to figure out the genotype of two dragons given that all of their offspring have two legs. Students could perform “thought experiments” on the computer, altering the genes of either parent, and then breeding them and observing the result. They could also use a special kind of “magnifying glass” to view the chromosomes of any organism. We logged what steps the students took, and what tools they used.

Looking over the process data from the two-legged dragon challenge, we found a wide variation in the way students went about the task. Some students bred the same two parents over and over, apparently hoping for success just by chance; others perseverated on an incorrect model (e.g., if both parents have two legs, so will their offspring), seemingly unable to think outside the



box. Still others approached the task systematically, examining the chromosomes of parents and offspring, varying only one parent at a time, and reasoning their way to the correct answer.

Once we had identified these different behaviors, we developed algorithms that enabled us to classify every student's investigations along a spectrum from "systematic" to "haphazard." We found a statistically significant correlation between a student's process score on this task and her subsequent learning gains as determined from the post-test. Moreover, this correlation persisted whether or not the student actually succeeded—in other words, the process variables predicted learning gains¹ even when the student failed to accomplish the task. Even more surprising—and gratifying—was the extent of the "transfer effect" from this task. The post-test included some items that were directly related to the content underlying the two-legged dragon task (i.e., monohybrid inheritance, or the inheritance of a single characteristic), together with many other items that were not. One might expect a student's process score to correlate more strongly with the proximal items than with the test as a whole. In fact, the reverse was true: performance on the task was more predictive of the overall post-test score than of the score on the directly relevant items.

The task described above is not unique; many of our activities contain similar "hot spots"—tasks that are open-ended and complex enough to engage students in authentic inquiry while giving us a glimpse into their cognitive processes. We have identified such "teachable moments" in each of the science areas covered by the project. And each of the hot spots examined so far shows the same intriguing correlation with learning gains, as measured by conventional assessments. The next step is to look for "learning progressions." Do students improve their model-based reasoning skills as they progress from one activity

to the next? And do such skills transfer between scientific domains? Does the tenth grader who learns to reason with models in genetics apply that skill when he encounters the model-based gas laws unit in junior year chemistry? We don't know yet, but we have enough data to find out.

Any Number Can Play

The IERI program that funded this work imposed two nearly mutually contradictory constraints. The research was to be methodologically rigorous and carefully controlled, yet it had to be potentially scalable to very large numbers of students and schools. We addressed these contrasting requirements by constraining our intervention to be entirely computer-based, thus minimizing local variability and the need for extensive professional development. We then made it freely available on our website to any school. When schools downloaded the software, they were given the option to register with us and allow us to collect data from them. In return, we reported to each of these "contributing" schools regarding the performance of their students².

Over the period of the project, nearly 400 schools, located in over 20 countries, took advantage of this offer. However, many of these appear to have used the software offline (thus generating no data), and many others did not administer the pre- and post-tests. Nevertheless, 41 of the contributing schools did comply with these requirements, and we have subjected their data to the same analysis that we used for the 10 "member" schools that were officially part of the project. We were surprised to discover, in fact, that the contributing schools actually performed better than the member schools. For example, the 18 contributing classes that used the genetics model averaged a learning gain of 6.8 points, versus 5.8 for the member schools. This is a remarkable achievement, considering that the contributing schools received no support of any kind from the project³. Even allowing for the fact that the contributing schools were self-selected, their stunning success demonstrates the scalability of the technology and pedagogy.

Notes

- 1 The process variable score on this task accounted for approximately 10% of the variance in learning gains.
- 2 We encrypted all log files before transferring them from the schools to our server, and we maintained strict anonymity by assigning each student a unique ID number and stripping names from our database.
- 3 We conducted professional development workshops and provided monetary compensation to teachers at the member schools.

Implications

In Massachusetts students are not permitted to graduate from high school unless they achieve a minimum score on a largely multiple-choice test called the Massachusetts Comprehensive Assessment System, or MCAS. Many other states have similar requirements. Reliance on such traditional assessment tools can have two adverse effects: (1) the tests are artificial and at best serve as imperfect markers for real-world skills and abilities, and (2) an over-emphasis on improving test scores is causing many schools to spend so much time getting students ready for the MCAS that they have precious little left for teaching.

The experimentation with models demanded of students in the MAC project is a task much more analogous to real-world scientific methods than the act of answering a collection of unrelated multiple-choice questions. The inferences we make by observing how students perform model-based tasks turns them into insightful formative assessments that can guide teaching without disrupting it.

Some day, perhaps, the MCAS will be redesigned and the question-and-answer items of today will be recast as tasks involving manipulable models. When that happens "teaching to the test" will be the right and proper thing to do.

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LINKS *Modeling Technologies*



Modeling Across the Curriculum

<http://mac.concord.org>

Using Sensors and Models to Answer Discovery Questions

BY CAROLYN STAUDT AND STEPHEN BANNASCH

Science is a social construction of knowledge and practices based on observation, analysis, modeling, experimentation, and theorizing about the physical world around us. The *National Science Education Standards* states, “From the earliest grades, students should experience science in a form that engages them in the active construction of ideas and explanations that enhance their opportunities to develop the abilities of doing science.” Too often, however, science is treated only cursorily, if at all, in elementary grades and in a passive format: reading from a textbook. But even very young students can do much more, particularly when the science classroom includes probes and models. And that’s just what the Technology Enhanced Elementary and Middle School Science (TEEMSS2) project has been doing: designing activities with probes and models for students in grades 3-8.

In the Classroom: Temperature and Heat

Asked to study an event in which temperature changes and to think about how the changes relate to the flow of energy, fifth-grade students took temperature sensors and interfaces home from school for the weekend. Some compared the temperature of their dog’s mouth to their sibling’s mouth.

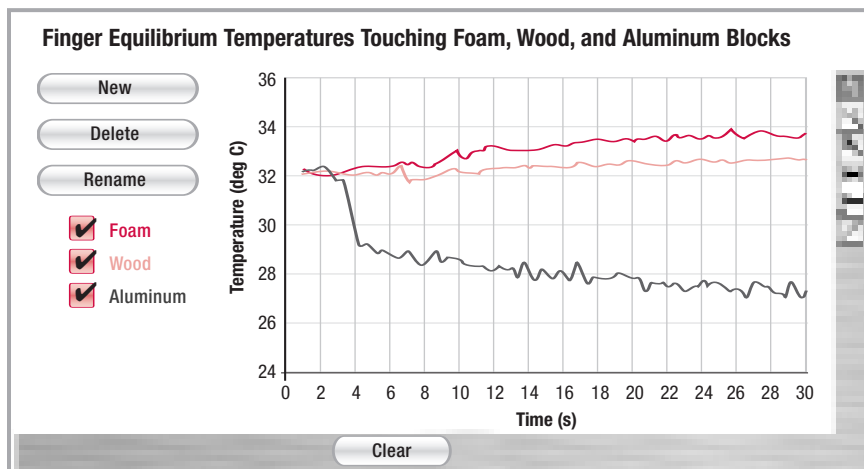
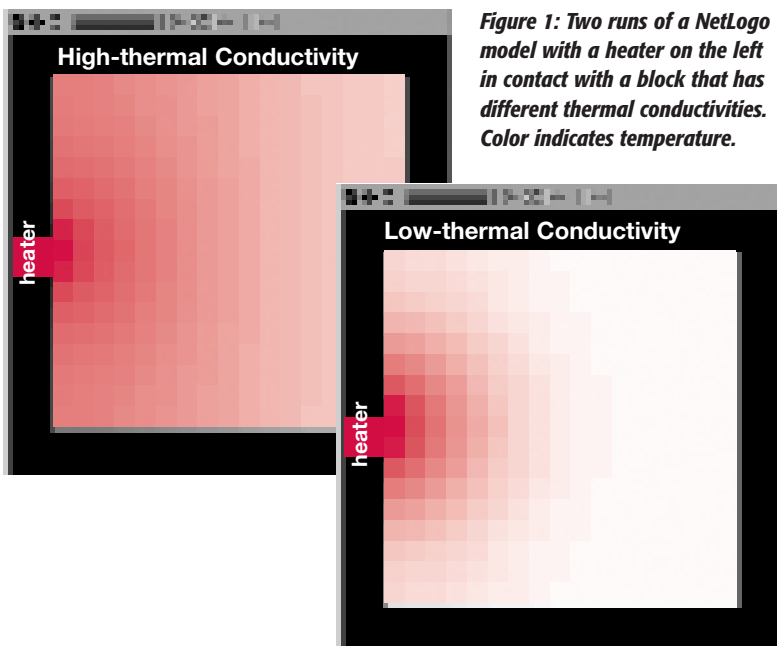


Figure 2: Results of students touching blocks made from three different materials (skin temperature vs. time).

Others compared the temperature of the sidewalk to the grass beside it. One young man tested the temperature under the covers of his bed throughout the night. His question was, “Why is it so much warmer when I wake up than when I first crawl into bed?”

He started the temperature sensor and tucked it under his blankets as he went to bed. Throughout the night, the interface recorded the temperature; when he woke, he had a graphical and tabular representation of the data. The graph showed an increase of temperature from the time he laid his head on the pillow to the time he woke. Questions surfaced as he reported to the class. Was the change in temperature due to the blankets? What was the temperature in the bedroom? Did it get colder as the night went on? Did he really become hotter throughout the night or did he just feel warmer?

The class discussion of his and other experiments produced a complex dialogue. The teacher guided the students to frame their new questions in forms that could be answered by further experiments. After collecting more data from numerous experiments, class discussions grew richer and more nuanced as brittle models of temperature and energy gave way to more robust models.

For instance, a commonly identified misconception regarding heat and temperature is based on the fact that a metal object at room temperature feels cooler than a wooden object, which in turn feels cooler than a foam object. The cognitive dissonance of a student’s experience of temperature differences and the “scientific” explanation that the objects are the same (room) temperature can lead to a student developing separate categories of “science” and “real” knowledge. A NetLogo model demonstrates this.

The block on the left (see Figure 1) is a simple model of a finger, which is both warm and generating heat. Students can change the thermal conductivities of the blocks with which the finger is in contact and indirectly investigate the flow of heat by looking at the temperature gradients that develop over time.

After viewing the model, students used a fast-response temperature probe to investigate the temperature of their own fingers, and discovered a wide range of finger temperatures among members in their class. Finally, students held the very small temperature probes between their fingers and three different blocks: aluminum, wood, and foam.

By collecting temperature data with a probe, students were able to easily see why the metal block felt colder (see Figure 2). The temperature data validated their experience. Indeed, their fingers did get colder touching the metal block. The aluminum block conducted heat away from their fingers much faster than the wood or foam blocks. In our NetLogo model the finger is modeled as a perfect heater with infinite thermal conductivity and mass. An improvement would be to model the finger with a finite thermal mass, specific conductivity, and a limited amount of heat input. This would allow the model to simulate the cooling and warming at the skin surface. However, using even our simple NetLogo model and the experiments with sensors, students learn that their bodies are heat engines and that heat flows faster through some materials than others.

Value of Probeware in the Classroom

Concepts	Benefits
Graphing	Real-time graphs connect a student's physical sense of the world with an immediate abstract representation. The meaning of different curves and rates of change become more concrete as patterns are associated with physical events and processes.
Understanding phenomena and issues of scale	Sensors can measure and display trends that inform deeper understanding of physical phenomena. Experiments with sensors can be repeated quickly.
Formulas and data transformation	By manipulating scales and axes, students implicitly begin to understand how a set of data can be transformed. By applying functional transformations to the data in graphical and tabular forms, higher-level connections are made between mathematical thinking and science.
Calibration	Calibration is a specific subset of data transformation, which is often very hard for students to understand. When students make their own probes, calibration is an inherent part of the activity.
Experimentation	When students are actively engaged with models and sensors, experimentation is a natural byproduct. Formulating a testable hypothesis is one of the hardest science process skills to learn. Repeated authentic inquiry-based experimentation is the only way these skills are developed.

Creating Your Own Probeware Activities

In addition to *TEEMSS2 curriculum* activities we created for three grade levels (3-4, 5-6, and 7-8) in five content strands, we adapted the technology so anybody can make and publish their own probeware activities (see "Do It Yourself" sidebar). The software is compatible with Mac OS X, Windows, and Linux computers, and with sensors and interfaces from five different companies. With a simple user interface—it's as easy as filling out a form—the power of probeware is at your fingertips. You and your students can answer your own discovery questions.

Carolyn Staudt is Director of the *TEEMSS2* and *ITSI* projects. **Stephen Bannasch** is Director of Technology.

Do It Yourself

Register for free at the *TEEMSS2 Do It Yourself (DIY) site* to create your own activity.

Start by viewing the **Activity Listing** for a list of already published activities, like "Mixing Different Temperature Water." **Show** will preview an activity in a web browser, while **Run** will create a custom Java webstart application, which will download and run the activity from your computer.

You can try the activity without a sensor by selecting the **Simulated Data** item in the **Probeware Interface** link on the left, and then clicking **Run** in the activity. Or select from one of five supported sensor companies.

When you first run an activity, select **New**. After using the activity and entering text or collecting data, choose **Save** in the file menu to save your work. To print the activity, first export it as HTML, then open and print it from your browser. You can also email or share any saved portfolio documents.

To **create a new activity**, choose the link on the Activity Listing page. A series of text fields allows you to add an Introduction/Discovery Question, materials, procedure, safety notes, and so on. Select a probe type from the pull-down menu. Click **Create** to save your new activity. Be sure to make it public so others can see and run it.

LINKS *Sensors and Models*



National Science Education Standards

<http://www.nap.edu/readingroom/books/nses/6c.html#csak4>



TEEMSS2 curriculum

<http://teemss2.concord.org/curriculum/>



TEEMSS2 Do It Yourself (DIY)

<http://teemss2diy.concord.org/>

Post-Textbook UDL Materials

The National Science Foundation has funded our plans to develop technology-rich science curriculum modules for grades 3-6, which acknowledges that students learn in different ways. The work at CAST, the Center for Applied Special Technology, has defined a flexible approach to teaching called Universal Design for Learning (UDL) that has had considerable success in teaching the language arts. This new project extends these ideas to science. The goal of this project is to use UDL principles to create practical science materials for students and teachers in inclusive classrooms.

The project will create seven inquiry modules around the theme of energy. They will ask questions such as "Why are there clouds?" and "What do plants eat?" Probes will support lab investigations and computational models will allow students to explore virtual environments. We will also develop graphing and modeling software that express data and relationships in text and language. Twenty-five classrooms in Acton, MA, Anchorage, AK, Maryville, MO, and Fresno, CA, will test the effectiveness of this approach through formative and summative evaluation. We hope these modules will inspire additional content and further development.

The Science of Atoms and Molecules

Because the theme of atoms and molecules runs through physics, chemistry, and biology, it provides a single framework that

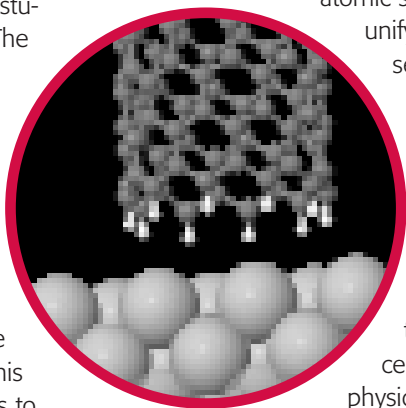
unifies these subjects. Our new "Science of Atoms and Molecules: Enabling the New Secondary Science Curriculum" project, funded by NSF, will develop four strands of atomic-scale materials that unify the curriculum sequence of physics, chemistry, and biology. The project will provide materials and professional development resources that allow high schools to implement a successful sequence of physics, chemistry, and biology as a unified and consistent progression. Curriculum materials will provide a progressive understanding of the importance of atomic-scale phenomena from fundamental atoms to complex biology. This approach is designed to guarantee better pedagogy, deeper learning, and longer retention.

Probes and Models Across the Curriculum

With our new NSF-funded "Probes and Models Across the Curriculum: Information Technology in Science Instruction" project, the Concord Consortium will prepare middle and high school students for careers in information technologies by engaging them in designing inquiry-based science activities that use computational models and real-time data acquisition and analysis.

Teachers from Boston, MA, Desert Sands, CA, and Olathe, KS, will meet in the summers of 2007 and 2008, plus online throughout the academic year to learn

basic electronics, programming, and design skills. They will learn how to teach students to install, configure, and use a wide range of sensors for measuring experiments with computers, and to use, modify, and create computational models. The skills learned will enhance each participant's teaching, while giving students a solid foundation for IT-based careers in programming, computer hardware, and software engineering.



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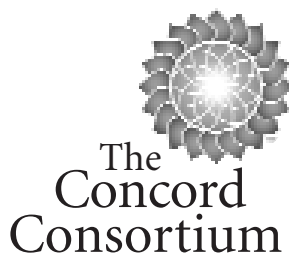
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