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REALIZING THE EDUCATIONAL PROMISE OF TECHNOLOGY

Probeware and the XO

Ubiquitous computers are coming and probes are close behind

BY ANDY ZUCKER, ALVARO GALVIS, AND ROBERT TINKER

The $100 computer will soon be a reality. The *One Laptop Per Child* (OLPC) effort led by Nicholas Negroponte has put new energy into the idea of a low-cost educational computer that could be used anywhere in the world. Today they sell for around $175, but are available only if you want to buy a few million. The OLPC team hopes to get the price down to $100 after a year or two of mass production. The point is that this represents the future—it's just a matter of time before all computers cost a fraction of what they do now.

The XO is an extremely innovative response to the needs of kids worldwide, with special features designed for rural areas of developing nations. The XO is light and attractive. It consumes very little power, so it runs a long time on a charge and can be powered by a hand crank or solar cells. It has no hard drive to crash; it uses flash memory instead for long-term storage. It has Wi-Fi for easy wireless connection to other computers and the Internet. And the display can be seen in the brightest sun. To keep the cost down, the OLPC group depends heavily on open source, both for its operating system (GNU/Linux) and applications.

Imagine what a revolutionary impact a computer like the XO could have in the hands of children worldwide. It is an encyclopedia, library, language tutor, multimedia communicator, and music maker. It is a powerful tool for science inquiry, too, particularly if it has probeware—software and hardware for real-time data acquisition and analysis.

continued on page 4

Inside

Potholes in the Road to Proving Technology

BY ROBERT TINKER

News Flash: Bridges Found Useless!

A research study just released by Professor Slam A. Bridge of the University of Southern North Dakota shows that bridges have no value. In side-by-side comparisons, a recent study proved that bridges have no advantage over roads. Researchers gave drivers the option of selecting either a bridge or a straight road. To make a fair comparison, the same length and height bridge and road were placed next to each other. Both were capable of handling the same traffic. So as not to give the bridge an advantage, there was no river or other obstacle to cross placed in their path. Professor Bridge found no significant difference in most measures: transit time, accidents, or preferences.

In an attempt to be "scientific," researchers hold everything constant except the presence of computers **... a senseless comparison.**

Educational technology is getting a bad name because of some bad research. Two varieties of bad research have recently received far too much press. These illustrate the "hobbled horse race" and "trivial treatment" fallacies.

The hobbled horse race

The ersatz bridge vs. road story is an example of the horse race genre of media research. In an attempt to be "scientific," researchers hold everything constant except the presence of computers and then look to see whether kids learn more. There is nothing magic about a computer. Its presence does not confer any inherent advantage, so this is setting up a senseless comparison.

In one early study of the value of probes, researchers designed two versions of the classic middle school lab of the cooling curve. The experiment involves placing mothballs in a test tube, melting them, and then cooling them in air. The temperature of the mothballs is measured while they cool and a graph is drawn. At the melting temperature, the cooling curve shows a distinct plateau that can be related to the energy released on forming a solid. The computerized version of this experiment can be done with smaller amounts, speeding up the process and allowing more experiments in the same time it takes to generate one graph by hand. The extra experiments can be used to show what a cooling curve looks like without a phase transition, so that when a plateau is observed, students realize that it is something to be explained. Experiments with other substances and mixtures can further enrich the probe-based lab.

None of this, however, is "fair." The researchers in question wanted everything held constant, so exactly the same experiment was done with and without the computer at the same pace with the same amount of mothballs. Furthermore, to ensure reproducibility, the students were drilled in exactly what computer options to use, what buttons to press, and shown what data to expect. Both versions of the experiment were very "cookbook," and students were repeatedly warned not to deviate from the procedures because of possible danger to themselves, the computers, or the experimental results. The results were inevitable—no significant difference in student learning.

More recently, it has become popular to question the value of computer-generated animations. A recent issue of *Education Week* (Viadero, 2007) presented this as a debate. The anti-animation viewpoint was represented by Barbara Tversky, Ph.D., whose review of research (see, e.g., Tversky et al., 2002) has a strong similarity to the bridge and probeware stories.

She concludes, "Yet the research on the efficacy of animated over static graphics is not encouraging. In cases where animated graphics seem superior to static ones, scrutiny reveals lack of equivalence between animated and static graphics in content or procedures; the animated graphics convey more information or involve interactivity" (summary, p. 247).

In reviewing the literature, Tversky throws out all studies in which students interacted with an animation or where there was more information in the animation than in an equivalent static graphic.

"In order to know if animation per se is facilitatory, animated graphics must be compared to informationally equivalent static graphics. That way, the contributions of animation can be separated from the contributions of graphics alone without confounding with content" (p. 251).

The only conclusion was that when animations and graphics are equivalent, there is no significant difference in learning. While this may be "fair" from a research perspective, it does not establish that computer animations are ineffective, only that when they are hobbled to match the capacity of static graphics, they are no better.

The more interesting question is whether highly interactive animations result in more effective learning of difficult concepts. Are there things that simply cannot be taught other ways? It seems obvious, for instance, that the intimate knowledge that students gain of the atomic world through experimentation with the Molecular Workbench software (see p.12) or learning about molecules by "roving" around them (see p.14) would be hard to duplicate with static drawings. It is difficult to imagine how a comparison with drawings would be fair, given how immediate, interactive, and flexible the software is. It conveys more information and provides many more opportunities for learning.

News Flash:
Lawn Fertilizer Found Useless!

In a careful, $10 million study of the effectiveness of fertilizing lawns, no effect was found. "This proves that fertilizers should be banned," said a leading environmentalist, Dr. I. M. Phony. The study involved 10,000 homes in nine different climates divided at random into fertilized and non-fertilized lawns. After a year, no significant difference was found in grass growth between treated and non-treated lawns as reported by the highly respected researchers who used sophisticated statistics. (Because of practical and cost issues, the amount of fertilizer in the treatment was limited to 17 ounces per acre per year.)

The trivial treatment

The fertilizer study sounds impressive until that last sentence sinks in. The amount of fertilizer is minimal. Of course they didn't see an effect, but the problem isn't the fertilizer, it isn't the statistics, it is the study design. The researchers didn't make a large enough treatment to have an effect. The only correct conclusion is that you need more fertilizer than they used to cause a measurable growth. This is an example of the "trivial treatment" fallacy.

In April of 2007, a $10 million Department of Education study of 15 software products made front page news across the country. A headline in the *Washington Post* read, "Software's Benefits on Tests in Doubt: Study Says Tools Don't Raise Scores." The congressionally mandated study included nearly 10,000 students in more than 130 schools randomly selected by teacher. The major finding, as the *Post* headline suggested, was that test scores were not significantly higher in classrooms where the software products were used. This sounds like a body blow to educational technology until you realize that this study had a trivial treatment.

Teachers typically used the software about 10% of instructional time over the course of a year, which is much less than recommended by the vendors that supplied the products being tested. For example, students used the sixth grade math products for about 17 hours per year. Over 180 school days, that would average less than six minutes daily, a trivial treatment.

The Department of Education made another huge error in the design of the study; they used multiple-choice tests. To see a small effect, you need a sensitive instrument. Good software is particularly valuable in producing gains in higher-order thinking skills, which are notoriously difficult to measure with multiple-choice tests. Research from the Technology Enhanced Learning of Science Center that we co-founded has recently shown convincing gains in student thinking as a result of well-designed activities (Linn et al., 2006). Like the DoE study, the tests were delivered to large numbers of students at the end of a year during which students had 10-20 hours of exposure to the treatment. The instrument had both multiple-choice and open-response items. An analysis of the former showed no effect, but significant gains were visible when open-ended responses were analyzed with a rubric that looked for correct ideas that were linked meaningfully—a practical definition of higher-order thinking. Had the DoE researchers used similarly well-designed open-ended questions and scoring rubrics, they might have had a chance at seeing some effect.

Average readers will conclude from the publicity generated by the Department of Education study that educational technology is useless. They will use the study to support opposition to school funding for computers and other technology.

Twenty-five years ago, a study of computer-assisted instruction examined classrooms in which students used software for either 10 or 20 minutes per day, and found positive effects on test scores. Why did we need to spend $10 million to learn again that it takes significant amounts of time to increase students' test scores?

What's needed

If thoroughbred technology is not hobbled, it can sweep past the plow horses educators have been using. In the right conditions, with well-designed, highly interactive software, probeware enhances student explorations and animations give unparalleled educational value. We do need more studies to demonstrate this to skeptics, but not studies that use minuscule treatments and poor measurement instruments.

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

REFERENCES *Proving Technology*

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Note: Thanks to Andy Zucker for his analysis of the Department of Education study.

Probeware—*continued from page 1*

Probeware on the XO

Probeware is one of the most valuable applications of computers to science education, as shown by extensive research. When used with good learning activities, student experimentation with probeware is better at conveying many difficult science concepts than any other approach. The National Assessment of Educational Progress has seen a correlation between probe use and science achievement. Recent data from our <u>*Technology Enhanced Elementary and Middle School Science*</u> (TEEMSS) project shows that probeware also works with elementary students. In some cases, we were able to show that the TEEMSS approach is better than conventional instruction.

All this positive research is no surprise to educators who understand the importance of hands-on inquiry in science, technology, engineering, and math (STEM) education. As a result, science teachers have begun to demand that any computer used in STEM have probeware: sensors, an interface, display and analysis software, and associated curriculum materials, preferably integrated with the analysis software.

The National Assessment of Educational Progress has seen a **correlation between probe use and science achievement.** In some cases, we were able to show that the TEEMSS approach is **better than conventional instruction.**

TEEMSS does all that and more. It consists of 15 science and technology learning activities for grades 3-8 that have been tested extensively. The underlying TEEMSS software is open source and most of it runs on all full-sized computers, and on handhelds that are equipped with Palm and Microsoft's CE operating systems. Probeware from any of the five manufacturers of interface hardware systems can be used with these, too. This high level of interchangeability is a boon to teachers trying to provide equipment for each lab station, because they can use almost any combination of probe equipment and computers they can round up.

When we heard about the $100 computer effort, we wondered whether it could be added to our list of supported hardware. Since last summer, we have been working with the OLPC group to add probeware to the XO using the TEEMSS technology.

Our standard desktop version of TEEMSS required more "hard drive" and dynamic memory than is available on the testing version of the XO. We reduced the amount of "hard drive" memory required by cutting down Java. However, we did not have time to analyze and reduce the amount of dynamic memory required. So TEEMSS software starts up, but it quickly uses up too much memory. The released version of the XO will have more dynamic memory, so we are optimistic our software will work on it.

Doing it yourself

Schools in rural areas of developing countries do not

Probes and portable computers are made for environmental investigations. The XO is only the latest in a line of portable computers that can get kids involved in exciting and engaging science.

have access to commercial probeware, nor are they able to pay for it. Therefore, to support probes inexpensively, the XO designers made it possible to use the microphone input for probes, eliminating the need for expensive interface electronics. In effect, the microphone input is a direct analog input that can be used for other sensors as well.

The plan is to provide an inexpensive kit containing a few key components from which kids, parents, or teachers could construct their own probes. Our *Information Technology in Science Instruction* (ITSI) project is developing just such a do-it-yourself kit for U.S. teachers on tight budgets. It not only provides an inexpensive and flexible way of creating probes, it introduces kids to electronics and the hardware side of information technologies. The ITSI kit gives us a low-cost approach to probeware that can be used with the XO anywhere.

The ITSI kit includes a light detector, some LEDs that also sense light, two temperature sensors, a magnetic field detector, and a small DC motor used to measure rotation. It will also include some electronics to convert the output of these sensors into a voltage that is compatible with the XO input. With some ingenuity, these basic sensors can be used to measure many different quantities. For instance, the guide for the ITSI kit will have suggestions on how to extract a pH indicator from red cabbage (a common low-cost science lab) and use it with the light detector and an LED to measure pH. We will also show how to use the DC motor as a distance detector by averaging and integrating its output.

All this technology can be a challenge to teachers. Not only are there technical details to learn, electronics to master, and software to become familiar with, there are new science concepts and new teaching strategies that are needed to take full advantage of the new functions made possible by the technology. We have all kinds of supports to help teachers become expert in this environment: well-designed materials, workshops, and online resources. The activities require no technical expertise to run and the do-it-yourself hardware is fully supported with instructional guides. We also use the best online teaching techniques in a short online course that provides all the required background.

TEEMSS also includes a do-it-yourself authoring environment for creating student activities. Using this, teachers are not restricted to the 15 activities we developed. It is easy to modify our activities or develop new ones. Modifying activities has proven to be a good way for teachers to learn the material, think about the pedagogy, and incorporate their knowledge of their students into the activities.

"Awesome!" "I see it now!"

Teachers and students alike raved about the TEEMSS activities.

"The students were very excited to use the handhelds and sensors. One student said 'I see it now' when the lesson was on how vibrations produce sounds."

"The sound unit was most engaging for my students. They already love music, so every time we learned something new, several students would run to tell the music teacher what they just learned about loudness or pitch."

"The students really were captivated by the use of the sensor and are convinced that it is much more accurate than their own fingers for measuring temperature."

"Students are excited about the sensors. They said it was 'awesome' and are asking about the next activity."

"Students all agreed that this was much more rewarding and they picked up on the concepts quicker than the traditional style of learning."

LINKS *Probeware and the XO*

One Laptop Per Child
http://www.laptop.org

TEEMSS
http://teemss.concord.org

ITSI
http://itsi.concord.org

For more on probeware in education, see:
www.concord.org/work/themes/probeware.html

Final thoughts

Probeware illustrates an approach to technology-enhanced education that needs to be part of any program that uses XO computers. While putting computers in the hands of millions of schoolchildren around the world is exciting, simply providing access to computers has little impact on learning unless it is part of a larger plan. Students learn best using well-designed flexible materials that provide guided exploration. Technology is necessary to enhance the range of options, but technology alone is not sufficient to generate educational gains. It requires excellent materials and guidance by well-qualified teachers.

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Computers and Clean Slates
Creating Interactive Learning Experiences

BY PAUL HORWITZ

When Alice Liddell, known to the world as the inspiration for Lewis Carroll's *Alice in Wonderland* was a little girl, one mark of a good student was to bring a "clean slate" to school. The slate in question started as a piece of roofing tile, though by Alice's time special school slates were manufactured for the sole purpose of having students write on them. The beauty of the slate—a revolutionary piece of educational technology in its time—was that it could be erased and used over and over again. And so it was that good students (and Alice was surely one) were expected to come to school each day with their slates washed, ready for new information, and devoid of any memory of whatever information they might have contained the day before.

> In our effort to make **powerful, general-purpose tools** have we lost sight of the fact that our students may misuse the tools, misinterpret their results, or simply become bored and **drift off to the nearest interactive game?**

A lot of "modern" educational software is like Alice's slate. You run it, play with it, possibly learn something from it, and then forget it as quickly as it forgets you. Like the slate, the computer has no agenda, nothing in particular that it's trying to teach, and no expectation that students will do anything in particular with it. Which is just as well, since whatever they do will leave no trace—neither student nor teacher will ever be able to refer back to what was done, much less infer what was learned through interaction with the computer.

Take a grapher, for instance, that ubiquitous little tool that produces graphs from equations or data. An egregiously non-scientific sample (the first 10 of more than 2,000,000 Google hits for "grapher") comes up with many examples of the type that would make great educational tools, but not one that actually sets up problems, helps students solve the problems, and remembers what they did so that next time they'll get different problems, selected on the basis of prior knowledge or gaps in their understanding.

Why is that? Why have we apparently regressed to Alice's time in our use of information technology for education? In our effort to make powerful, general-purpose tools available to them, have we lost sight of the fact that our students may misuse the tools, misinterpret their results, or simply, in the absence of an explicit challenge, become bored and drift off to the nearest interactive game?

Learning from games

The comparison to games is instructive. Games have a purpose. Whether it is shooting as many bad guys as possible or figuring out how to work the teleporter, games have definite goals and subgoals, and they reward inquiry and problem-solving skills in immediate and tangible ways. They offer assistance where and when necessary, and most importantly they remember who you are when you return; they put you right back in the action where you left off, without wasting your time on stuff you've already mastered or giving you challenges that are too advanced.

So why don't educational tools do the same thing? There are three obstacles, at least: (1) it isn't easy to come up with problems that are challenging and fun and also teach something, (2) it isn't easy, when someone is struggling to solve a problem, to figure out what is wrong and react appropriately, and (3) it isn't easy to create and maintain the technological infrastructure that enables the system to keep track of each student's progress.

In tackling obstacle number one, the first step is to recognize that we are not designing software, we are creating an *interactive curriculum*. In the case of a grapher, for instance, this means that we don't just worry about creating an interface that enables a user to make graphs easily, instead we must start with what the student is supposed to know already and what we would like her to get better at, and then create an activity that helps her learn. We have to start by realizing that the grapher is not the end product, it is the tool with which to create many different, targeted learning activities.

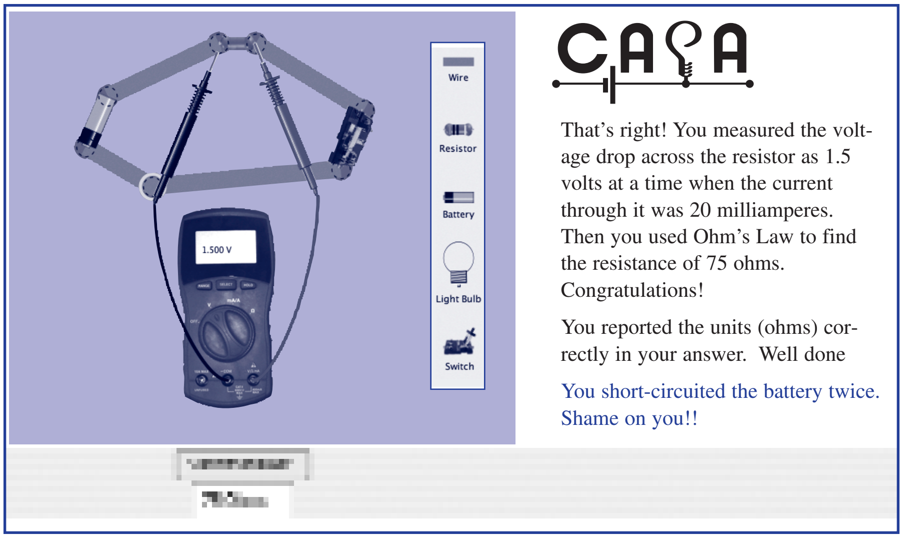
Listening to students

The second obstacle—figuring out when a student is having difficulties—

LINKS *Computers and Clean Slates*

- **TELS Center**
  http://www.telscenter.org
- **Computer-Assisted Performance Assessment**
  http://capa.concord.org
- **Physics Educational Technology**
  http://phet.colorado.edu/web-pages/index.html

This example of a scripted assessment activity reports not only a student's answers, but also how she obtained them.



flows from the first: a good activity should monitor a student's actions and make reliable inferences. We can look to see whether successive attempts have been getting her any closer to the goal. We can check whether she is changing only one variable at a time in a systematic fashion, or trying everything at once. If we see counterproductive behaviors, we can offer context-sensitive help. We can watch for improvement as the activity progresses, and generate insightful reports for the teacher.

The third obstacle—the lack of infrastructure—is obvious, but difficult. Supporting interactive learning and assessment activities requires the maintenance of a database that preserves privacy and confidentiality, yet is accessible by students and teachers alike. The answer to the problem lies in the technology itself, which has to become robust and user-friendly enough to be maintainable in a school environment. The Concord Consortium is actively working to make this happen.

Through our association with the University of California at Berkeley's <u>TELS Center</u>, we are helping to develop a powerful new software architecture that supports the persistence of students' online activities so that they can access their portfolio, do their homework, or post questions for their study group from any platform at any time. Only when these functions are commonplace will the technology become an accepted and essential part of school life.

Next steps

What does it take to turn a general-purpose tool into an interactive learning experience for a student? In software terms the answer is straightforward; you simply write scripts that embed the tool as a component. The scripts configure the tool (for instance, displaying a "target curve" for a graphing activity), and implement the activity (e.g., describing how to react when the student submits an answer). In practice, though, the script may not be able to communicate with the tool in the right way. Seemingly routine commands like "Don't redraw the curve until the user has clicked on the button" may be impossible to implement if the grapher program hasn't foreseen the need for them. Luckily, it is usually easy to change the program to accommodate such needs, if it is open source.

An open source license generally permits one to alter a program, provided that one makes the revised version available under a similar open source license. And that is exactly what we have done on our <u>*Computer-Assisted Performance Assessment*</u> project, using an applet from the <u>*Physics Educational Technology*</u> group called Circuit Construction Kit. The Circuit Construction Kit is a remarkably powerful, open-ended software tool that enables a student to build any circuit containing wires, bulbs, batteries, resistors, or switches, and to measure the voltage or current at any point in the circuit. However, the program does not pose a specific problem and consequently cannot judge how a student is doing. From our point of view, it's a program that calls out for scripting.

And that is what we have done. Our initial script (one of many we intend to build) is very simple: it puts a resistor on the screen and asks the student to measure its resistance. It tracks what the student is doing and waits for her to submit an answer. When she does, the program reports on and critiques not only her answer, but also the manner in which she obtained it. What circuit did she build, how and when did she use the meter, and how did she use the measurements to calculate the answer?

Alice's 18th century slate eventually evolved into a workbook that could guide her activities and keep a record of what she has done. The computer-toting students of the 21st century deserve no less.

We are helping to develop a powerful new software architecture that **supports the persistence of students' online activities** so that they can access their portfolio, do their homework, or **post questions for their study group** from any platform at any time.

Paul Horwitz *(phorwitz@concord.org) directs the Computer-Assisted Performance Assessment project.*

Roving Around Molecules

BY ROBERT TINKER AND QIAN XIE

The 3D geometry of atoms and molecules is difficult to grasp, but this knowledge is important. How can we give students a firsthand experience at the atomic level? Impressive demonstrations with expensive equipment have shown the value of computer-based molecular visualization to provide virtual experiences; there is strong anecdotal evidence of the educational value of such immersive environments. We have now brought this experience to the desktop with the *Rover*, our newest addition to the Molecular Workbench, the Concord Consortium's award-winning molecular dynamics package. Interacting with the Rover can help students internalize accurate mental models of atomic-scale phenomena and develop an expert's ability to reason more effectively at different levels. No special glasses, prisms or other paraphernalia are required.

> Interacting with the Rover can help students **internalize accurate mental models** of atomic-scale phenomena and develop an **expert's ability to reason.**

Rover parts

Navigation. In order to simulate the ability to move around molecules, we needed a way to show molecules from any perspective. This requires very fast software, because the illusion of smooth motion requires that the screen be redrawn at least 20 times per second, each time from a slightly different perspective.

We have been using a Java molecular viewer called Jmol to display 3D objects. *Jmol* is ideal for Rover because it is fast, open source, and written in Java, our development language of choice. Jmol, however, did not originally support navigation—the ability of the user to move into and around molecules. Jmol simply views molecules from the outside. The molecule can be rotated and even displaced, like using a zoom lens, but always with the perception that the molecule is "out there."

In order to overcome this limitation, we collaborated with the current chief Jmol developer, Robert Hanson, Ph.D., to add navigation functionality to Jmol. Because it is open source software, we did not have to duplicate the considerable work and creativity that has already gone into Jmol. Instead, we were free to concentrate on adding the functionality we needed. Our additions are now available to Jmol users worldwide.

This new navigation capacity allows the user to appear to "fly" around molecules and explore structures from the inside. Even moving through macromolecules with thousands of atoms is handled smoothly and realistically.

Animation Studio. The Molecular Workbench is more than a simulation, it is also a complete system for authoring and delivering learning activities that use the simulations. As exciting as it is to move through a molecule, there are problems for end users if they get lost in the complexity and overlook significant features. Authors need ways to guide student experiences so that they navigate to the important parts of a molecule. To enable this, we created an Animation Studio, which allows authors to create virtual tours through molecules. A virtual tour consists of a series of scenes set by the author to introduce the fascinating molecular world and guide students through various structural patterns from different perspectives.

Embedded annotation system. Once students arrive at an interesting place in a molecule, they may need to be prompted with a question or given additional information. Inspired by Google Earth, we developed a system for inserting annotations into the molecular world. An annotation key, which is a customizable object embedded in the 3D space, can be attached to an atom, bond or chemical group, as illustrated in Figure 2. A link to other molecules or to a web page can be inserted into the annotation. The annotation capability is useful not only in making molecular explorations instructive, it also permits us to build a web space for any user to leave an

A side-by-side comparison of the default mode and the navigation mode

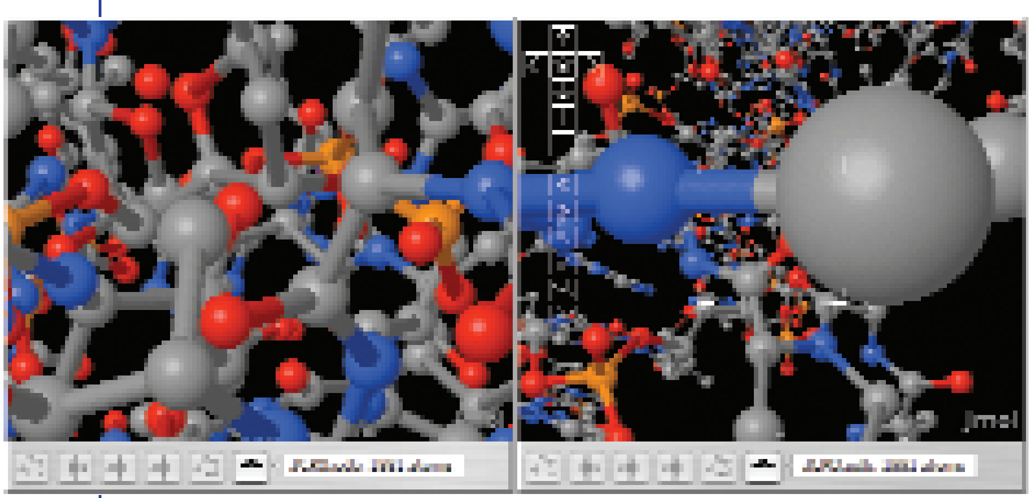


Figure 1 compares the original 3D capacity (left) with the navigation view (right) for the same molecule. The full 3D experience of molecules in motion is spectacular.

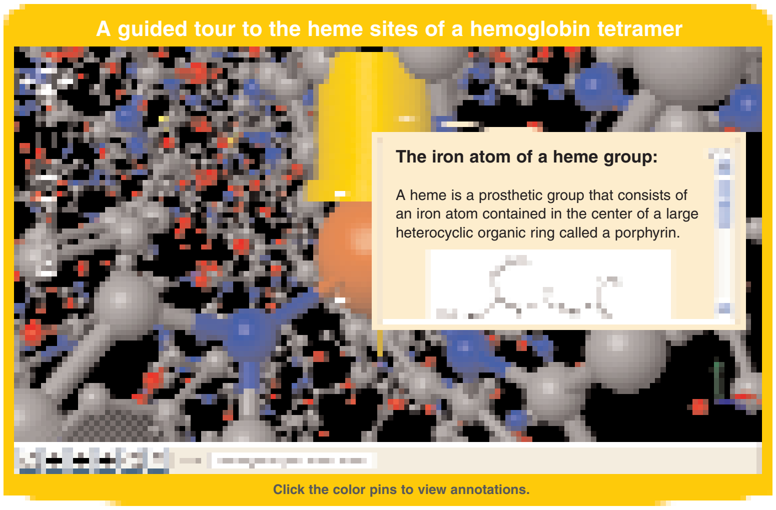


Figure 2. A pushpin key and its associated annotation. When the user navigates to the key and clicks on it, the annotation content comes up. The author of an activity controls the content of the annotation, which can contain text and graphics, plus links to other points in the molecule or web pages.

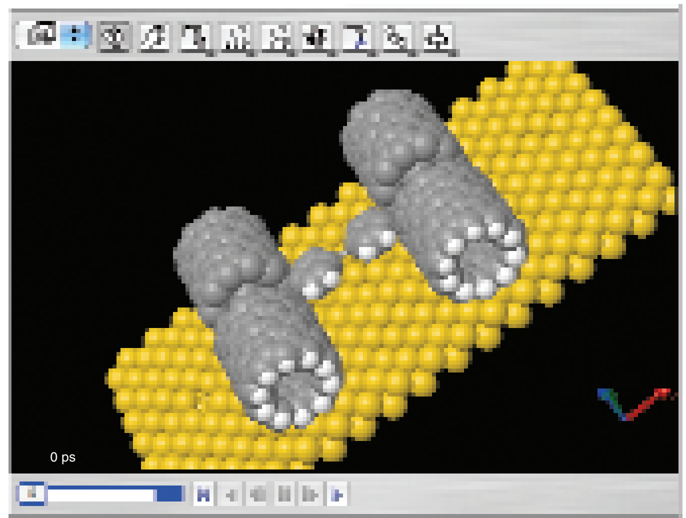


Figure 3. A molecular nano car with tires made of four short carbon nano tubes, all created using the Molecular Constructor. It sits on a gold crystal and can roll.

annotation to any molecule, which will then be seen by other users, similar to Google Earth or Wikipedia.

Molecular Constructor. This universal 3D constructor can be used to build any kind of molecule. Unlike other molecule builders, this tool works directly in 3D—there is no 2D-to-3D conversion. Most elements in the periodic table are supported with appropriate force field parameters determined according to their chemical properties. Building blocks such as amino acids, nucleotides and basic hydrocarbon molecules are provided for the user to rapidly sketch up complex molecular systems. A variety of tools are provided for the user to build 2-, 3-, and 4-body bonds, run energy minimization for selected atoms, cut/copy/paste molecules, and more. Figure 3 shows an example of what can be created with the Constructor.

Molecular dynamics simulator. All of Rover's capacity is embedded in the Molecular Workbench, a molecular dynamics package that models the motion of molecules—their continual thermal vibrations and their responses to any applied forces. Consequently, students can see any Rover molecules in motion. Because the Constructor is part of Molecular Workbench, students can build molecules and then instantly run a simulation. This will reveal, for instance, whether a molecule is thermodynamically stable at different temperatures and how it might fold. This approach can potentially be useful in conveying the knowledge of chemistry in a trial-and-error way, similar to building a bridge and testing how much load would cause it to collapse. Figure 4 shows a snapshot of a molecular dynamics simulation on the subject of stereochemistry of the ethane molecule.

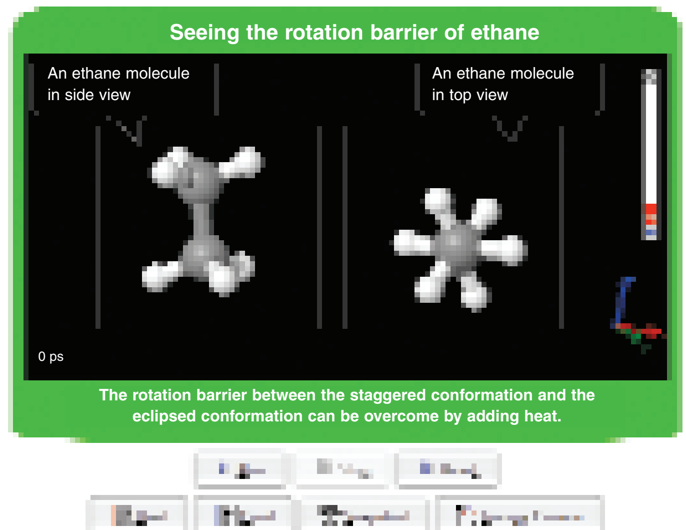


Figure 4. Part of a molecular dynamics simulation of ethane rotation. Two views of the same molecule are show as it vibrates and rotates. At low temperatures, the molecule is trapped in the position shown, but as the temperature increases, the two ends can turn independently.

Conclusion

Getting a feel for the three-dimensionality of molecules is essential in the exploding fields of biotechnology, nanotechnology, modern medicine, genomics, bioinformatics, and electronics. These fields require a conceptual understanding of the physical properties of collections of atoms and molecules and the ways in which interactions at the atomic scale relate to macroscopic properties. This understanding is difficult to acquire and is often shrouded in advanced mathematics and obscure terminology. The new Rover capacity in the Molecular Workbench provides an alternative, direct, and appealing route to this understanding. And "flying" through atoms and molecules is just plain fun!

Robert Tinker *(bob@concord.org) is President of the Concord Consortium.* ***Qian Xie*** *(qxie@concord.org) is Senior Scientist at the Concord Consortium.*

LINKS ***Roving Around Molecules***

Molecular Rover
http://rover.concord.org

Jmol
http://www.jmol.org

The Science of Atoms and Molecules

BY ROBERT TINKER

"A dramatic revision of the science curriculum can generate a truly revolutionary way of teaching science in U.S. high schools." **—Leon Lederman, Nobel Laureate in physics**

"You mean there are air molecules hitting my arm all the time?" **—9th grader after having worked with a Molecular Workbench model**

If you could shrink by a factor of a billion (think "Honey, We Shrunk Ourselves"), you would enter a very hostile environment. Since gravity is negligible compared to other forces, you would feel like you were floating in space—until something hit you. The instant you arrived, you'd be knocked unconscious by a speeding atom. In fact, millions of atoms and molecules would be slamming into you at the speed of jet planes every second!

Here, everything is in violent, random motion and when things heat up, everything moves faster. Atoms and molecules constantly flex, vibrate, and crash into one another too quickly to comprehend. If you brought along a stop-action camera that slows time down a billion-fold, you would see that collisions are perfectly elastic, so atoms bounce off one another without losing even the tiniest fraction of their energy. The dominant force is electrostatics—if two atoms carry as little as one electron's charge, they exert huge forces on each other. Even uncharged atoms exert some electrostatic forces on each other. Without these forces between neutral atoms, there would be no liquids or solids, no life, no planets.

While contemplating that amazing fact—boom!—you hear a small explosion. That's the energy released when a chemical bond is formed. Sometimes this is accompanied by the release of a packet of light; other times the resulting molecule careens off a nearby molecule like a rocket. The reverse happens, too—a light packet or a high-speed collision can break up a molecule. Mostly, however, the molecules are strong, rigid blobs. Water molecules and many others of these objects have charges on their surface. You don't want to be between two molecules with these surface charges because they slam together and hold fast. Time to reenter the macroscopic world—fast!

> The science of atoms and molecules is the **fundamental basis of biology.** Atoms and molecules are also central to modern chemistry, earth science, electronics, nanoscience, forensics, and **all the interdisciplinary fields** like biochemistry, space weather, and plasma dynamics.

Adventures in the atomic world

The atomic world is very different from our macroscopic world. Indeed, many of the instincts you have developed about the way things work do not apply at the atomic scale.

It is critically important to understand the science of atoms and molecules because it is at the heart of modern science and technology. "A concise summary of the last 100 years of science is that atoms and molecules are 85% of physics, 100% of chemistry, and 90% of modern molecular biology," claims Concord Consortium board member Leon Lederman.

For instance, biology increasingly depends on the science of atoms and molecules. Many biological processes are understood in terms of molecules and their physical interactions, such as biomolecular synthesis, energy pathways, evolution, and ecosystems. We know precisely the mechanics of muscle contraction, how one errant molecule causes sickle cell anemia, and which molecular errors cause some cancers. The science of atoms and molecules is the fundamental basis of biology, and the future of understanding disease and developing new treatments. Atoms and molecules are also central to modern chemistry, earth science, electronics, nanoscience, forensics, and all the interdisciplinary fields like biochemistry, space weather, and plasma dynamics.

Incorporating atoms and molecules

The critical missing content in most introductory science curricula is a solid set of materials that addresses atomic-scale science. The basic physics of atoms and molecules needs to be introduced early so that chemistry can take advantage of these concepts. Similarly, biology needs to leverage student understanding of atomic-scale physics and chemistry to address key introductory molecular biology concepts.

The logic of this approach explains why Leon Lederman and many others have been advocating "Physics First"—a reordering of the introductory secondary science sequence that places physics before chemistry, which is then followed by biology. But this new sequence solves nothing if it doesn't incorporate the science of atoms and molecules.

Too often schools that have tried Physics First simply rearrange the sequence of topics without changing them. Without addressing atoms and molecules and exploiting the connections among the courses, this reordering will not significantly improve the science curriculum and can result in a net decrease in understanding.

The "Science of Atoms and Molecules" Provides the Answers

Since the atomic world is seldom taught well, we are developing the *Science of Atoms and Molecules*, a new project that has four strands of atomic-scale materials and professional development resources that unify the secondary curriculum sequence of physics, chemistry, and biology.

As part of this project, we are creating a *Molecular Concepts Inventory* to measure student understanding of the science of atoms and molecules. Answer these true/false questions, then find your score online (sam.concord.org/mci).

TRUE	FALSE	
❑	❑	Solids melt because the forces between atoms get weaker as the temperature increases.
❑	❑	All atoms attract one another with a short-range force.
❑	❑	ATP is an energy source because the high-energy phosphate bond releases a lot of energy when it is broken.
❑	❑	The temperature of a group of atoms or molecules is determined by their average kinetic energy and nothing else.
❑	❑	Atoms in solids are held in place so they do not move as fast as liquid and gas atoms at the same temperature.
❑	❑	Heat energy in a material consists of the disordered motion of its atoms or molecules.
❑	❑	Creating a chemical bond lowers the potential energy.
❑	❑	Evaporation causes a liquid to cool because evaporating atoms are, on average, hotter than the liquid they leave.
❑	❑	Ions dissolved in room-temperature water are surrounded by ice.
❑	❑	Oil and water don't mix because the oil molecules repel water molecules.

Molecular Workbench to the rescue

Our *Molecular Workbench* software simulates the basic properties of atoms, molecules, ions, photons, chemical bonds, biological molecules, and a wide range of forces. All sorts of phenomena emerge from these properties, such as phase change, evaporation, diffusion, latent heats, chemical reactions, black body radiation, and self-assembly. Students can play around with Molecular Workbench models and get a feel for the strange world of atoms. However, just as in the macroscopic world, without some guidance, students miss much of the value of the Molecular Workbench experience. To help, we created a sequence of activities for biology students. Other activities are designed for technical colleges and high schools as a bridge between science and technology courses.

When we studied student learning with Molecular Workbench in middle school through college, we found that students learned content while also getting better at using models. Students appeared able to use their understanding of the atomic-scale world to reason their way to correct explanations of new situations. There is some indication that students retained their model-based learning for a long time. By going deeper, it appears that students gained insights that persisted and helped them understand new problems.

LINKS *The Science of Atoms and Molecules*

- **Molecular Workbench**
  http://mw.concord.org/modeler
- **Science of Atoms and Molecules**
  http://sam.concord.org
- **Molecular Concepts Inventory**
  http://sam.concord.org/mci

Creating a better introduction to science

We are currently developing activities for high school Physics First curricula that start with the physics of atoms—how they are constructed and the relationship between their average kinetic energy and temperature. We introduce the all-important forces between atoms, which give rise to a potential energy, and the central idea that the sum of kinetic and potential energies is conserved. Chemical bonds are explored, along with the idea of electronegativity, which causes charge separation and explains the strong attraction of polar molecules. Color, fluorescence, spectra, and many other phenomena are explained by discussing how light can interact with atoms and molecules while conserving energy. These ideas provide a firm physical basis for many biology topics. As a result, the entire treatment of physics, chemistry, and biology is more logical and, therefore, a better introduction to the conduct of science.

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

Understanding Earthquake

BY AMY PALLANT

GEOLOGISTS COLLECT DATA about Earth and its tectonic plates. Indeed, we live on shaky ground. In 2004, the Indian Ocean earthquake triggered a series of devastating tsunamis, killing large numbers of people and inundating coastal communities across South and Southeast Asia. While geologists know that earthquakes cannot be predicted, they continue to explore the patterns of earthquake activity around the world.

The following activity was developed for the *Information Technology in Science Instruction* (ITSI) project, whose goal is to help middle and high school teachers prepare diverse students for careers in IT by engaging them in exciting, inquiry-based science projects that use computational models and real-time data acquisition.

In this earth science activity your students will study data—the same data geologists use—and look at patterns of earthquake magnitude, depth, location, and frequency in order to discover the patterns of distribution associated with different types of plate boundaries.

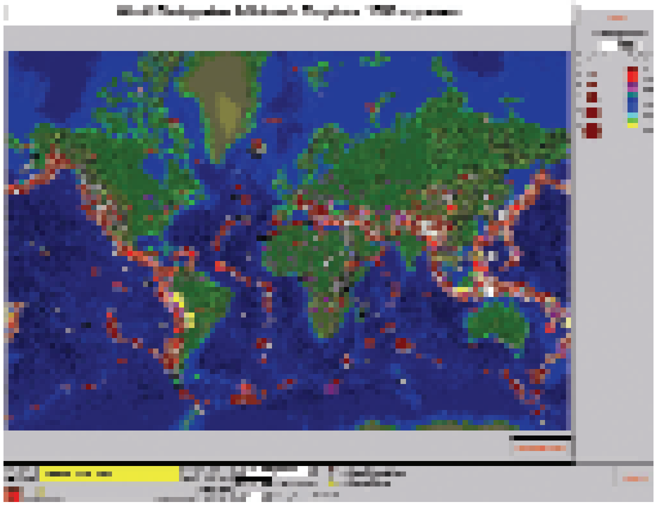


Figure 1: Seismic Eruption software as it begins to plot earthquakes greater than 5.0 in magnitude. The size of circles represents earthquake magnitude; depth is represented by different colors.

Current earthquakes

Software called Seismic Eruption plots all the earthquakes and volcanic eruptions that have occurred around the world since 1960. These data are linked directly to the most current data collected by the U.S. Geological Survey (USGS).

Observing data

The goal of this introductory activity is for students to take note of the patterns of earthquakes around the world. It is best not to focus on individual earthquakes, but rather to look at the overall pattern of the earthquakes.

1. Have students observe the earthquakes as they are plotted around the world. Click the **PLATES** button in the lower right to view the Earth's plates and the **KEY** button in the upper right for a description of the boundaries.

Launching the Seismic Eruption Software

- Download Seismic Eruption from http://www.geol.binghamton.edu/faculty/jones/
- After the opening screens disappear, click the **WORLD** button in the center of the screen to watch all earthquakes that have occurred in the world from January 1, 1960, until the present time.
- Set the program to display **6 MONTHS/SEC** by clicking the up arrows on the speed control below the map.
- Go to the Control Menu, select **TIME TO PAUSE AT END…** A dialog box will appear. Type as many 9s in the box as you can. Click **OK**

Note: Seismic Eruption software runs on Windows 95/98/NT/2000/XP. Seismic Eruption was developed by Alan L. Jones, Ph.D. We gratefully acknowledge his assistance.

LINKS *Monday's Lesson*

ITSI
http://itsi.concord.org

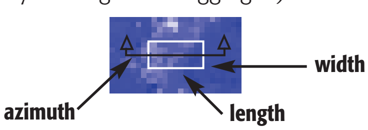
Activity Along Plate Boundaries

2. Students should look for characteristic patterns of earthquakes along each type of boundary. For example, which boundaries have the most frequent earthquakes? Which have the deepest earthquakes? Do the earthquakes occur in wide bands or narrow bands along the boundaries?
3. In pairs, have students brainstorm different ways to describe what they see.

Creating cross-sections

Challenge students to go deeper—literally! Have them create cross-sections along each type of boundary. Students should take notes about a) the relationship between *magnitude* of earthquake and *depth* of earthquake to plate boundaries, b) the frequency of earthquakes along each type of boundary, and c) the location of earthquakes relative to each type of plate boundary.

1. Go to the Control Menu and select **SET-UP CROSS-SECTION VIEW.** (See Figure 2.)
2. Click anywhere on the map. This will cause an icon like the one below to appear. (Move the icon to any location by clicking and dragging it.)



3. Increase the length to 1500 and width to 500 by using the arrows or typing in numbers.
4. Click the **REDRAW** button and watch what happens to the icon.
5. The azimuth changes how the red line is drawn in comparison to the bottom of the screen. Change the azimuth to 20, 0 and -20 and click **REDRAW** each time.
6. Place the cross-section tool anywhere along a plate boundary. Be sure to place the azimuth so that it is perpendicular to the plate boundary and crosses over the plate boundary. The boundary should be in the center of the icon. Then click **OK.**
7. View the cross-section by going to the Control Menu, selecting **MAP VIEW/3-D/CROSS-SECTION** and clicking **CROSS-SECTION VIEW.**

Figure 2: Cross-section view.

Table 1

	Latitude	Longitude	Depth (km)	Magnitude
1/1/2006	35.13	-117.56	3	2.9
1/3/2006	37.44	-117.08	5	3.1
1/7/2006	32.49	-115.44	5	3.7
1/7/2006	32.49	-115.44	5	3.7
1/9/2006	44.92	-112.36	10	3.1
1/9/2006	32.17	-115.80	9	3.2
1/12/2006	33.93	-117.80	9	2.7
1/13/2006	37.47	-118.78	11	3.1
1/15/2006	37.32	-118.31	8	2.8

Analyzing

Students are now prepared to evaluate their descriptions. Have students summarize what they have learned about the occurrence of earthquakes along different plate boundaries. What do the depth, magnitude, location and frequency tell about the dynamic movement along each boundary?

Hold a discussion about the certainty of their descriptions. Is each description good enough to cover data collected by other students? Have students look at data from other students along each boundary. Do students recognize that the distribution patterns provide evidence for the different types of movement along plate boundaries?

Applying understanding

The earthquake data you've been studying was collected by the USGS and imported into the Seismic Eruption software. The USGS also provides numerical information about each earthquake, including magnitude, date and time, location (latitude and longitude), and the depth in kilometers.

Table 1 includes a small subset of data from the USGS Earthquake Database.

1. Examine the data and determine what type of plate boundary the data represents.
2. List three ways the data confirms your conclusions.

Ask students to think about the depth, magnitude, and frequency of earthquakes that occur along the different boundaries.

The key here is to look at all the data. Only then can students make sense of the patterns of earthquake activity and better understand the shaky ground on which we live.

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How Do Students Learn from Models? Case Studies in Guided Inquiry

BY ROBERT TINKER

We knew that we wanted to use global climate change to capture student interest because learning is always more vivid if it connects to real-world issues. Climate change is in the news and will be for a long time to come, so students are certain to be curious about the topic. From an educational perspective, the topic is loaded with opportunities to teach science content, science inquiry, computational models, statistics, and technology (not to mention politics, economics, and social studies).

But we were stymied by the complexity of climate modeling. The debate about climate change is really a debate about models: how they are constructed, what variables are used, how they are verified, and what their results mean. How can we give middle and high school students an introduction to these issues without overwhelming them with detail? And more practically, how can we find an appropriate model that we can afford with limited resources?

"We" in this case is a team of researchers who are participating in the Center for Technology Enhanced Learning of Science (TELS). One of several Centers for Teaching and Learning funded by the National Science Foundation, TELS studies student learning with highly interactive environments using a knowledge integration design. The science content provides better ways to teach state and national standards that teachers have found difficult. The materials are software-based and generate student data used in our research.

We initially looked for existing climate models that we could use or adapt, but all had fatal problems. Either they didn't run on both Mac and Windows operating systems or they were too complex or clunky. Since their source code was unavailable, we couldn't fix these limitations. We did find a set of mathematical equations that might work, but saw no way of implementing them in the TELS platform. We almost settled for a Flash animation that showed some of the issues involved in the greenhouse effect, but we wanted a better approach that supported student experimentation with the model.

LINKS *Model-based Learning*

- **Center for Technology Enhanced Learning of Science**
  http://www.telscenter.org
- **NetLogo**
  http://ccl.northwestern.edu/netlogo
- **Modeling Across the Curriculum**
  http://mac.concord.org
- **AgentSheets**
  http://www.agentsheets.com
- **StarLogo v3.0**
  http://education.mit.edu/starlogo-tng
- **WISE**
  http://wise.berkeley.edu
- **Pedagogica**
  http://pedagogica.concord.org

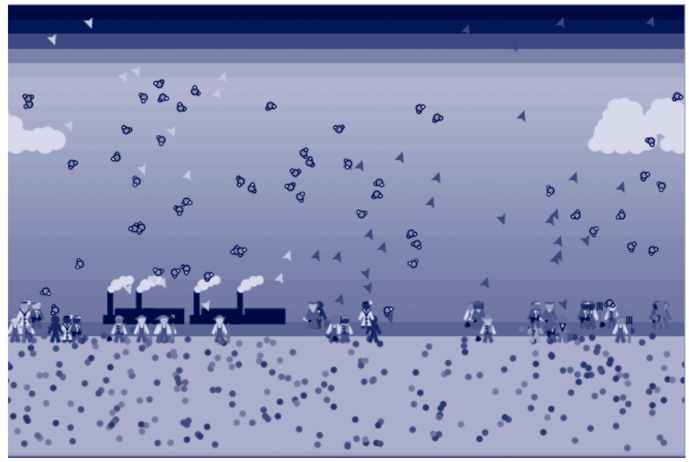

Figure 1: A snapshot of the NetLogo Global Climate Change model. When run, there is a lot going on, but the model has tools for supporting careful investigation. It can be slowed down and run with different settings.

NetLogo and StarLogo to the rescue

What at first we thought was too difficult—namely, creating our own model from scratch—proved to be quite easy using NetLogo. We had already used NetLogo in our Modeling Across the Curriculum project, so we had the technology needed to integrate any NetLogo model into the TELS platform.

It is a mistake to think that languages for children, such as BASIC, AgentSheets, HyperScript, and Logo are toy languages, suitable only for kids. As Seymour Papert has pointed out, Logo has "no threshold, no ceiling." NetLogo is an implementation of Logo that supports multiple "turtles" (programmable objects), which can be anything. In the Global Climate Change model, for example, the turtles are used to represent packets of solar energy, people, clouds, and carbon dioxide.

The joy of Logo in general and NetLogo in this case is that it is easy to create a sophisticated application with minimal effort. Having never programmed in NetLogo, it took me only a weekend to create working versions of the two climate models needed in the project. The models have various slider inputs, a stunning animated graphic representation (see Figure 1), and graphical outputs. Most importantly, the graphic helps explain what is going on. Students can trace the fate of a packet of sunlight. Such a packet might get reflected off a cloud or absorbed by the Earth. The more that are absorbed, the hotter the Earth gets. As it warms, infrared energy packets are emitted that go through the clouds, but can be reflected by greenhouse gasses. In the second model, population growth, factories, and pollution abatement strategies are introduced. Students can discover, for instance, the minor impact of clouds and the connection between birth rates and climate.

Eric Rosenbaum has created StarLogo versions of the Global Climate Change models. *StarLogo v3.0* is an open source cousin to NetLogo that features a graphical programming interface that makes it even easier to develop code. In StarLogo, programming consists primarily of combining programming blocks that fit together only in certain ways. As a result, it is impossible to make a syntax error, and it is far easier to visualize the function of program parts (see Figure 2).

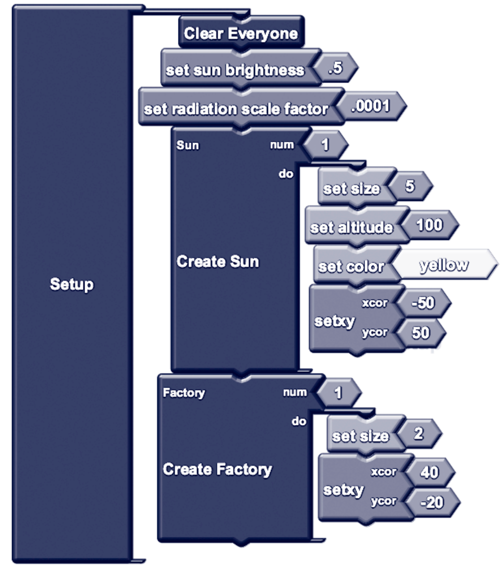

Figure 2: Part of the Global Climate Change program using StarLogo's graphical programming language. Programming consists of dragging the right blocks into the structure and entering some values.

Guiding model-based learning

Students learn many science topics best through *guided exploration*. Exploration without guidance is too chancy and takes too long. Guidance without exploration is just another form of direct instruction that relies more on memorization than reasoning. From this perspective, the Logo climate models, while lovely, represent an incomplete learning experience. They need to be converted into guided activities by providing help, context, background, commentary, challenges, and opportunities to share models and ideas. The models need to be set up with different initial conditions and questions.

All these additional functions are provided by the TELS platform, which represents a synthesis of *WISE* and *Pedagogica*. WISE, developed at the University of California at Berkeley, is a stable web-based environment that features easy activity development and good reporting for teachers and researchers. Unfortunately, large applications like NetLogo that are best executed on client computers do not fit easily into WISE. Pedagogica, developed at the Concord Consortium, is a client-side environment that is completely flexible, but requires a programmer to write student activities. Their synthesis into the TELS platform represents an important milestone that will simplify authoring and delivering guided inquiry activities that use powerful client-side applications like Logo.

The Global Climate Change model is used in two TELS activities: a middle school Global Climate Change activity designed and studied by Keisha Verna and a high school Chemical Reactions activity created and studied by Jennie Chiu. They recorded how long students used the models, how many times they ran the model, and how they explored the variables. Both TELS researchers found evidence that experimentation with the model, combined with other features of the activities, resulted in deep, integrated learning.

Conclusions

Out of a conviction that the very best way to understand a model is to build it, NetLogo and StarLogo were designed to make it easy for children to construct models. But model building may not be the best way to understand complex topics like climate change. Inexperienced children can easily get the model wrong. It takes care and insight to create a model with the right combination of variables, equations, and controls to incorporate the central ideas and generate realistic behavior.

If the goal is to convey some particular math or science content, guided exploration of a completed model is a far more effective and efficient educational strategy. This suggests that languages like the Logo dialects should be thought of as development tools for materials designers who are attempting to convey complex concepts such as global climate change. For us, the fact that Logo can be embedded in a platform like TELS is particularly important because a full range of scaffolding and assessment options can then be used. The combination of the evolving TELS platform and modeling languages like NetLogo and StarLogo greatly simplify the creation of activities that guide student learning of complex content.

__Robert Tinker__ (bob@concord.org) is President of the Concord Consortium.

A student says …

"By actually controlling the CO_2, clouds and infrared energy, you could understand what goes on when the CO_2 or sunrays increase or decrease. When you use the 'Watch Sunray' feature, it helps you to understand how the sunrays are harbored in the Earth and then later released as infrared energy. Using all of the features helps to see how the Earth's atmosphere is affected by chemicals and other things floating in the air."

A teacher says …

"This unit was a hit and I will use this year after year. The models resemble the interactive screen the students are used to since most of them are gamers or use various multimedia devices. The models help students visualize the effects of greenhouse gases, which in turn helps them understand the concept at a higher level. When students analyze, then they are at the highest level of thinking. I think the model did this for the students."

NEWS at Concord Consortium

Technology CAN Improve Education!

*Recent results support our basic tenet that technology-enhanced student activities can improve education (*www.concord.org/research).

Young Learners Learn Better with Probeware

Can students as early as grade three learn science with probeware? Many educators assume that elementary learners are not ready for sophisticated probes, sensors, and the associated quantitative data, arrays of numbers, graphs, and analysis. Our classroom data shows precisely the opposite.

We equipped 40 diverse grade 3-8 classrooms throughout Missouri and in other locations with probe-based science and technology activities and studied their learning. Non-computer tests given before and after each unit showed that in all cases, students learned important, standards-based concepts. Compared to the year before using our materials, our approach resulted in more learning in most cases.

Modeling Skills Accelerate Learning

We followed over 12,000 high school students for up to three years as they worked with model-based learning activities in traditional science courses. Our software reported each student's every move, from their manipulations of computer-based models to their use of visualization tools and their answers to embedded questions. Analysis of this detailed information revealed patterns in the students' use of models that correlate with other aspects of their learning, such as their scores on traditional question-and-answer assessments. Students who were systematic in their use of models learned the content better and were able to apply their knowledge more broadly than students whose manipulations of the model were haphazard. We also saw a longitudinal effect: students exposed to our materials in one year performed significantly better than their peers when they encountered another set of model-based activities in a subsequent year, even though the scientific domains of the two units were entirely different.

Anyone Can Learn About Atoms and Molecules

The conventional wisdom is that atoms and molecules are too abstract and intangible to be tackled before high school chemistry, but the Molecular Workbench (MW) is so interactive, and makes atoms and molecules so tangible, that we embarked on a series of studies to test that hypothesis.

Our studies indicate that middle, high school, and community college students can use MW-based materials to construct robust mental models of core content such as the random motion of atoms, the relationship of temperature to kinetic energy, gas laws, states of matter, dissolving and diffusion, and protein folding. In all classes, from 8th to 13th grade, misconceptions about atomic-scale phenomenon virtually disappeared and student content scores increased significantly.

Having demonstrated that it is possible to teach important concepts by interacting with MW, we are now looking at whether student learning persists and whether this approach is better than others. Preliminary studies indicate that students retain clear mental models of the activities for at least six months. Students who engage in MW activities showed improved content knowledge, compared to those who learned similar materials without the models.

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