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INSIDE

Students use GenScope, one of the modeling programs developed to manipulate genetic information in order to understand how changes at one biological level affect life at another.

Designing Computer Models that Teach

by Paul Horwitz

Of all the species on earth, *Homo sapiens* is the only one, so far as we know, that uses models. We invent models for many, often conflicting purposes: to provide parsimonious descriptions of observed phenomena, to predict what will happen under prescribed circumstances, and sometimes to explain why things happen the way they do. Models are the indispensable tools of modern science, and increasingly they run on computers, which enables us to predict, and to varying degrees control, the exact landing spot of a Mars probe, the three-dimensional configuration of a molecule, or the chance of rain tomorrow. Such uses of models, in fact, have given rise to a new kind of research, aptly described by the phrase "computational science."

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GenScope—genscope.concord.org

The Concord Consortium

Editor
Robert F. Tinker

Managing Editor
Lee McDavid

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The Concord Consortium
37 Thoreau Street, Concord, MA 01742
(978) 369-4367, FAX (978) 371-0696
info@concord.org
http://www.concord.org

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Designing Computer Models

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But whereas the research laboratory has embraced computer-based models as an aid to understanding, the same cannot be said for schools, where pre-college science classes all too frequently concentrate on teaching facts, rather than scientific reasoning. The question naturally arises, then, whether the use of computational models in a school environment might not help students, literally, to think like scientists. Indeed, several efforts have been made to introduce models similar or identical to those used in research into the classroom.

Varieties of models

Scientific models may vary quite dramatically across disciplines. A physics model, such as the theory of relativity, is very different from a model in biology, such as Mendel's model for genetics. As a result, scientists in different disciplines often differ considerably as to what they consider a model, and how they judge its utility. Physicists tend to place great store in the simplicity of a model, its fundamental nature, its explanatory power. Those models are particularly prized that start from an axiomatic base (e.g., Newton's Laws of Motion or the constancy of the speed of light), particularly so if they can be shown to apply to a wide range of phenomena. Biological models, in contrast, are judged primarily on their explanatory power. They are expected to be approximate, somewhat ad hoc, and to admit of exceptions.

Teaching models

Computational models used for research in whatever discipline are not necessarily much good for teaching. The design of a good teaching model starts with several simple but important questions. What exactly do we expect the students to do, and when they do it, what do we think they will learn? What do the students think they are doing when they use the model? What semantics or purpose do they associate with their manipulations of it?

A question one should always ask of any piece of software is, why do this on a computer? In the case of computational models, what educational value does the computer bring to the enterprise, and what special role does it play that couldn't have been filled as well or better in some other way?

A good teaching model should be simple, but not too simple, capturing the essence of the professionals' mental models of the domain, but stripped of unnecessary complications. It is also useful if the model is modifiable — either by the teacher or by the students themselves — which may enable it, among other things, to change to meet the needs of students as they become more versed in the subject matter. For example, at first we may want certain aspects of the model to be inspectable by the students; later on, we may wish to turn this feature off, in order to force the students to make inferences indirectly by experimenting with the model.

A useful starting point for designing a computer-based model for teaching something is to choose the set of objects and manipulations that it will incorporate. If we choose them carefully, these will be familiar and interesting enough to "jump start" the students' learning, but a formless and unstructured environment will not be enough to sustain the process. Often, we must impose a higher level semantics and purpose on the model. It is not enough, in other words, that the stu-

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Mendel—www-hpcc.astro.washington.edu/mirrors/MendelWeb
Newton—www.newton.cam.ac.uk/newtlife.html

dents be able to manipulate the objects. They must have a reason for manipulating them, a reason that motivates their investigation and connects it to the science concepts we hope they will learn. This semantic overlay can also serve to link the features of the computer model to their analogs in the real world — a crucial aspect of the learning process and, as we shall discuss below, by no means an automatic consequence of students' interactions with the model.

Thinking along these lines, my colleagues and I at The Concord Consortium (and earlier at BBN) have created several game-like environments that pose problems to students and offer them powerful computer-based tools with which to solve them. Each tool embodies an underlying model of a specific scientific domain, and each offers a set of representations and affordances appropriate to that domain. In each case, the student learns the domain by exploring the operation of the model. We call these open-ended exploratory environments "computer-based manipulatives" (CBMs for short) in order to emphasize their close pedagogic analogy with the mathematics manipulatives commonly used in the elementary grades.

a good teaching model should be simple, but not too simple

Choice of representations

In choosing what objects to represent, the educational software designer is not limited to those that would be accessible in real life. On the computer we can show students many things that are ordinarily invisibl. And we may choose, for pedagogical reasons, to hide others that would normally be visible. Nor is it simply a matter, for example, of showing the user things that are too small to be seen with the naked eye, or too difficult or hazardous to approach. Many scientific models, for example, include abstractions (e.g., the center of mass of a collection of objects) that are invisible because they are not real, but are often more important for understanding the working of the model than the real objects themselves.

Often we can get an educational advantage from hiding information that would normally be available to students. Here is an example. Imagine that our goal is to help students understand, at a qualitative level, the nature of elastic (energy and momentum conserving) collisions between point particles. We could simply tell the students to watch the motions of the particles very carefully and try to figure out what is going on. This might work, but it would be a lot more motivating if we simply made one of the particles invisible and challenged the students to locate it by studying the motion of the visible particles. Every so often one of these will bump into the invisible one and make a sharp turn. From a careful study of the motion — and a pretty detailed knowledge of the dynamics of the collision — the students should be able to figure out where the invisible particle is and where it is going. To dress this activity up and make it more fun, we could invent a tool that acts like a "butterfly net." Once a student has figured out where the invisible particle is, the object is to place the net over it and click the mouse button. This action turns the invisible particle visible and freezes all motion. If the invisible particle lies within the butterfly net, we award the student a point, create a new invisible dot at a random location with a random velocity, make the butterfly net just a wee bit smaller, and start the cycle over.

Choice of affordances

Just as we may take away an ability they would normally have, for pedagogical purposes, we sometimes enable students to do things on a computer that they would not be able to do in real life. GenScope is a manipulable model of genetics that we have

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Atomic-Scale Models

The Key to Science Education Reform

by Robert Tinker

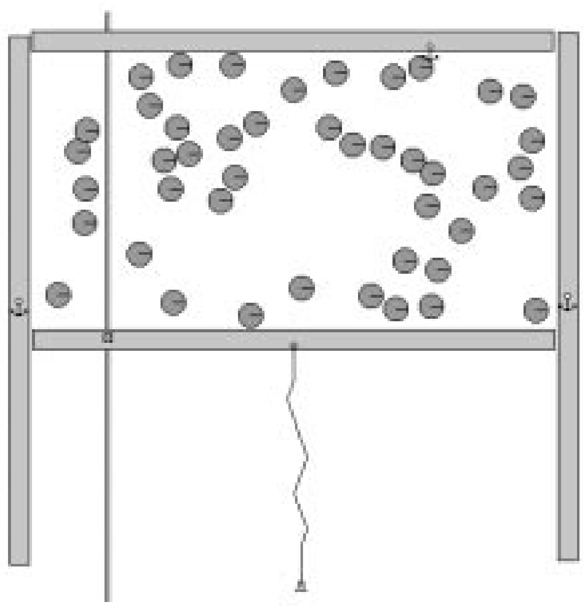
[The structure of matter] may have the most implications for students' eventual understanding of the picture that science paints of how the world works. And it may offer great challenges too. Atomic theory powerfully explains many phenomena, but it demands imagination and the joining of several lines of evidence. Benchmarks for Science Literacy

Even though there is a good argument for a total restructuring of high school science, when I first heard of the effort to start with physics and then introduce chemistry and biology, I was appalled.

It's not that this sequence doesn't make better sense; modern biology is built on chemistry and both subjects are built on physics. How can a student, for instance, understand protein structure without understanding solubility, a key concept of chemistry that depends on the physics of electrostatics at the molecular level? But the flaw in the proposal is that high school physics, as usually taught, is almost irrelevant to chemistry and biology. Physics is almost always synonymous with classical Newtonian mechanics: projectiles, pulleys, inclined planes and the like. For physics to be of any use to chemistry and biology, it must address atomic physics: the structure of atoms and molecules and their interactions, material which is rarely part of any introductory physics course at the high school or college level, even the overrated AP Physics curriculum.

So, it must be understood that implicit in the proposal to reverse the sequence of high school science courses is a totally new conception of physics, something the leading advocates of the "physics first" concept, such as Nobel Prize winner Leon Lederman, agree is necessary.

The new sequence allows biology and chemistry to be based on an atomic view of the world. The new role for physics is to provide that perspective. This is a huge challenge that will require far more curriculum change for physics than is needed in biology or chemistry. An approach is needed that is accurate without being overly mathematical. Much of atomic physics can be treated classically, but students also need an acquaintance with the strange world of quantum mechanics. Although students will have only limited mathematical skills to analyze these concepts, statistical concepts will have to be addressed. The challenge will be to equip students with the important insights while avoiding too great a reliance on mathematics.



This Interactive Physics model shows a "gas" of circles about to be compressed by a spring-loaded piston. Each object is created much as they would be if they were drawn in a graphics application. The fun begins when you run the model and the objects move according to physical laws. In this case, the piston pushes on the gas and the gas pushes back, making the piston oscillate. But even though energy is conserved, the piston eventually slows down and moves randomly. Do you see why?

This new science curriculum needs to address a set of topics that currently lacks an accepted name. I recommend using the term "atomic-scale models." This is better than "atomic theory," as used in the Benchmarks for Science Literacy, and similar terms used in the *National Science Education Standards* that risk confusion because scientists use these to describe the quantum mechanical description of electron orbitals in atoms. "Kinetic molecular theory" (KMT) is widely used in education, but it generally applies only to physical phenomena that do not involve chemical bonds, atomic forces, or atomic level interactions with light. This term should be quietly buried because it covers more than kinetics, applies to atoms as well as molecules, and is a model, not a theory.

While atomic-scale models pro-

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Leon Lederman—www-ed.fnal.gov/arise/arise.html

National Science Education Standards—books.nap.edu/html/nses/html

Benchmarks for Science Literacy—www.project2061.org/tools/benchol/bolframe.html vide an essential foundation for the new science curriculum, they are difficult to teach. Extensive research shows that using carefully designed instructional strategies, it is possible to teach middle school students KMT. It is questionable, however, whether it's worth the effort because, as usually taught, KMT does not have unifying power and fails to help students reason about related effects, such as thermal conduction, change of state, or the compression of gases. For example, one excellent study found that KMT does not help students understand thermal conductivity and the superiority of the fluid flow model of heat. In another study, prospective teachers failed to use KMT to explain evaporation and condensation. In both studies, the learners were unable to reason from the model.

This inability to reason from the KMT model is not surprising. Most of the reported successes with KMT test only whether students can produce the correct atomic-scale description for a given macroscopic situation. This measures memorization, not reasoning. For instance, students in one study learned to draw reasonably accurate atomic-level pictures of solids, liquids, and gasses, but there was no evidence that they could use these pictures to explain or predict phenomena. Doubtless, this "theory" appears to students as extra mental baggage that is difficult to remember because it is counterintuitive and doesn't explain anything. Because of these difficulties, the national education standards recommend delaying the introduction of atomic-scale models until the end of eighth grade or the beginning of ninth grade.

While this may be good advice given traditional instructional strategies, computer-based modeling tools can help students understand what is happening at the atomic level. By giving students manipulable computer-based models, we suspect that even young students can understand key concepts of atomic-scale systems. Using these models, students can explore the relationships between atomic forces, random motion, and a wide range of phenomena. Models can be built that demonstrate gas laws, condensation and evaporation, solubility, crystallization, protein conformation, and much more. This should give students a powerful understanding that has a broad range of applicability.

There are at least three software packages (supported by Macintosh and Windows operating systems) that educators can use today:

Interactive Physics. This powerful simulation environment sold by MSC Software can be applied to atomic models. It has the advantage that it is easy to use and modify. Educators on small budgets will appreciate that it can also support instruction in more traditional classical dynamics. In fact, this ability to move between macroscopic mechanisms and atomic-scale atoms and molecules might help remove some of the mystery of the latter. (See illustration, page 4.)

StarLogoT. Derived from Logo, this free programming language is optimized to support large numbers of independent "turtles" that can interact according to rules supplied by the user. The fact that it is a language that the user can see and alter makes the models particularly transparent. This may have great value to learners with some familiarity with programming. For the majority of learners who are unfamiliar with programming, models with good user interfaces can be created and shared. One of many models already available is Gas Lab (see also page 9). This model can be used to explore a wide range of gas properties. By adding electrostatic forces, an even wider range of atomic models can be built. (Read Uri Wilenksy's article and his *Monday's Lesson* on StarLogoT, starting on page 6).

Molecular Dynamics. This new package was developed by Stark Design specifically to support learning a range of atomic-level ideas. It has a very clean interface and a series of optional modules that illustrate specific concepts using both two- and three-dimensional models. Molecules and bonds are not supported. The full set of modules is pricey, but a free introductory version is available. The lack of documentation and user controls, however, might make this appear as an impenetrable black box to students. You can read about this application in Scientific American.

Each of these modeling packages has drawbacks for teaching atomic-scale concepts. We hope to encourage the developers of these programs to address the specific needs of students in a physics-first curriculum. We suspect that learners need flexible environments like these that support electrostatics, molecular bonds, and interactions with light. Once we study student learning with these environments, our expectations will have a strong empirical foundation. @

Robert Tinker is president of The Concord Consortium. bob@concord.org

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Interactive Physics—www.krev.com/products/ip.html
StarLogoT—www.ccl.tufts.edu/cm/starlogoT
Scientific American—www.sciam.com/1999/1099issue/1099amsci.html
Gas Lab—ccl.tufts.edu/cm/models/gaslab.html
Molecular Dynamics—www.starkdesign.com/sciam

Modeling Emergent Phenomena with StarLogoT

by Uri Wilensky

Everywhere we look, we see regularities, patterns, order. Many of these patterns have a kind of haunting beauty: the growth of a snowflake crystal, the perimeter pattern of a maple leaf, the advent of a summer squall. Other patterns, such as the dynamics of the Dow Jones or of a fourth grade classroom, seem messier, inchoate, yet still exhibit a familiar and recognizable general "shape." The characteristic shape can unfold in space or in time, sometimes striking and unmistakable and sometimes more hidden, needing probing observation or ingenious experiment to uncover it.

Why is there so much pattern in the world? While grappling with this question in full would take us far afield, we can start with a simple observation: large-scale patterns in the world are usually the result of the interactions of many smaller pieces that somehow combine in surprising ways to create the large-scale pattern. Such large-scale (macro-) patterns that arise out of the interactions of numerous interacting (micro-) "agents" are called "emergent phenomena" – that is, phenomena that emerge from interactions at a lower level or scale.

Visualize a flock of birds winging in the autumn sky or the amazing synchronized fireflies that blink in unison lighting up whole trees in the Far East. How do these patterns come about? All of these patterns are emergent; there is no leader bird which other birds follow, no conductor firefly leading the band – these patterns emerge out of the behavior of individuals and the adjustment of that behavior in interaction with other individuals.

The study of emergent phenomena is the principal occupation of a developing field of science, the study of complex dynamic systems. This broad new field seeks to understand how systems of interacting components evolve over time. In the minds of many, however, complex systems theory is not a new branch of science, but rather a new framework, a new perspective that allows us to see old scientific content in new ways. This new perspective and the methods it brings to bear have been adopted across a wide array of natural and social sciences. An understanding of complex systems is becoming an essential part of every scientist's knowledge and skills. The time has come for these ideas and methods to become a central part of *every* student's learning.

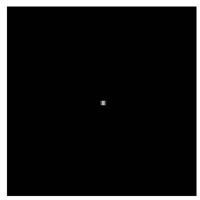

Figure 1. create-turtles 1000

Despite its adoption by practicing scientists, the complex systems perspective is largely absent from the K-16 curriculum. One reason for the slow transfer to schools is the heavy reliance of complex systems methodologies on the use of powerful computational technologies. By enabling the rendering, simulation and visualization of the evolution of complex systems over time, the computer has proved an indispensable tool for making sense of complex systems and emergent phenomena.

Most of the tools used by experts to explore complexity in their domain of interest are highly domain specific – designed for use by experts to study a particular class of phenomena. Until very recently, no general purpose tools existed for students to render and explore systems of many interacting parts that can exhibit emergent behavior.

At the Center for Connected Learning and Computer-Based Modeling at Tufts University, our goal is to create computer-based tools and curricula to enable students to make sense of complexity and emergent phenomena. I will now describe a set of tools developed with the support of the National Science Foundation that enable typical secondary students to engage and make sense of complexity and emergent phenomena.

A major project accomplishment was the development of a computer modeling language (and associated materials) that would enable learners, teachers and students to create dynamic models of complex phenomena. The language we developed, called StarLogoT[1], is now in use by thousands of students, teachers and researchers worldwide. StarLogoT is one of a class of new so-called multi-agent modeling languages (a.k.a. object-based parallel modeling languages or agent-based modeling languages) that have emerged from the complex systems community.

StarLogoT (and its mother language StarLogo[2]) is an extension of the computer language Logo in which a user "drives" a graphical turtle on a computer screen by issuing commands such as "forward," "back," "right" and "left." In Logo,

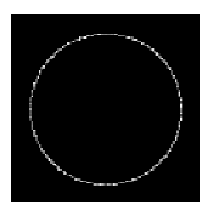

Figure 2. forward 40

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Center for Connected Learning and Computer-Based Modeling—www.ccl.tufts.edu
StarLogoT—www.ccl.tufts.edu/cm/starlogoT National Science Foundation—www.nsf.gov

typically, the turtle is thought to carry a "pen" and, thus, draws a line when it moves. In this way, children can create geometric shapes by giving motion instructions to the turtle. In StarLogoT, however, instead of driving a single turtle, the user can drive (or, perhaps better to say, orchestrate) thousands of turtles. Instead of drawing with pens, turtles

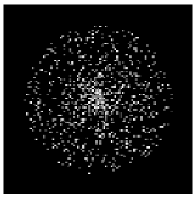

Figure 3. forward random 40

"draw" with their bodies. By that, I mean that the emergent shape of all the turtles' positions constitutes a drawing in StarLogoT[3].

Allow me to illustrate with a simple example in which turtles take the shape of little squares or points. If we initiate a StarLogoT session with the command "create-turtles 1000" then 1000 little squares will appear in the graphics screen. However, because they are initialized to start in the middle of the screen, they all pile on top of each other and appear as a single point (see Fig. 1).

If we then type the command "forward 40" all of the turtles move forward 40 screen units (see Fig. 2). Note that because the turtles were initialized with different "headings," (they faced in different directions) they made the shape of a circle. This is already a simple example of emergent behavior. The fact that there were enough turtles so that by random chance they were likely to fill the holes ensured that a coherent circle emerged from the motions of independent turtles.

At first glance, the reader might wonder how the turtles can do anything different and interesting if they all follow the same commands. The power of StarLogoT comes from the fact that each turtle is an independent agent. Because each turtle had an independent heading, they all moved in different directions when we typed "fd 40." Since it is possible for turtles to have as many states as the user likes, the response of turtles to the same commands can vary markedly.

In addition to this difference amongst turtles, each turtle does its own separate computation. To see how this makes a difference, we can type the command "back 40" to get all of the turtles back to the middle of the screen, then invoke the command, "forward random 40." The function "random" computes a random value between 0 and 40. Because each turtle does its own computation, each one gets a different value for "random 40" and thus will move forward a different amount (see Fig. 3).

(Beginning students often want to reverse this operation and try the command "back random 40." However, this has unexpected results. Try it.)

In addition to turtles, StarLogoT has a second kind of agent that we call a "patch." Patches are very much like turtles except that they are always around and do not move. The screen is initialized to a user resizable grid of patches. In other words, even though the graphics screen looks like empty black where there are no turtles, in reality the patches are invisibly lurking there waiting for commands.

If we type the command, "setpatchcolor green," all the patches will change their color to green (see Fig. 4).

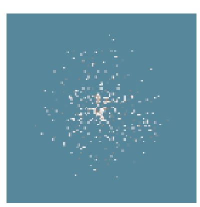

Figure 4. setpatchcolor green

Finally, if we type the command "if xcor < 0 [setpatchcolor black]" then all the turtles to the left of the origin turn black (see Fig. 5). The key point to keep in mind is that they do not do this because they are "told" to do it by a leader. They each examine their own position on the screen, determine if they are to the left of the origin and, if so, they turn themselves black.

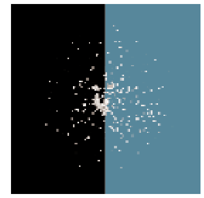

Figure 5. If xcor<0 [setpatchcolor black]

With these basic tools, we can now create models and dynamic simulations of many different kinds of complex systems. There is a saying that goes: "If all you have is a hammer, the whole world looks like a nail." With the powerful hammer of the StarLogoT language, it becomes easier to see emergent phenomena everywhere. Not only the classic emergent phenomena described in the complex systems literature, but many everyday and scientific phenomena can be viewed through the lens of emergent phenomena. While, at first glance, emergent phenomena seems like an exotic add-on to the curriculum, we see it as a powerful amplifier of understanding for virtually all scientific topics. By enabling us to make cogent and testable connections between the micro and macro, the individual and the collective, the element and the system, the new lens makes them easier to understand for novice and for expert learners alike. @

Uri Wilensky is Director of the Center for Connected Learning and Computer-Based Modeling at Tufts University.
oas@ccl.tufts.edu

FOOTNOTES

1 StarLogoT currently runs only on Macintosh computers. A multi-platform version, which we call N-Logo, will be available in early 2000.

2 StarLogo was originally developed at MIT. StarLogoT is an extension and superset of MIT's MacStarLogo.

3 StarLogoT "turtles" do not typically look like turtles. They are general purpose "agents" that can take on any shape.

Monday

Using Sta

by Uri W

Here are two examples of the kinds of models students can build with StarLogoT. The first example is a model of a simple predator-prey ecosystem — a popular model with high school students using StarLogoT. In a typical model, students model a predator (say a wolf) and a prey (say a sheep). They need to give rules to individual wolves and sheep so that they can move and interact. Many sets of rules are possible. A typical set of rules might assign an energy level to each wolf and sheep and decrease their energy when they move, increase their energy when they eat (wolves eating sheep). If their energy falls below 0, they would die. At every turn, they get a random number (roll an imaginary die) and if they are lucky they reproduce. (See Figure 1.)

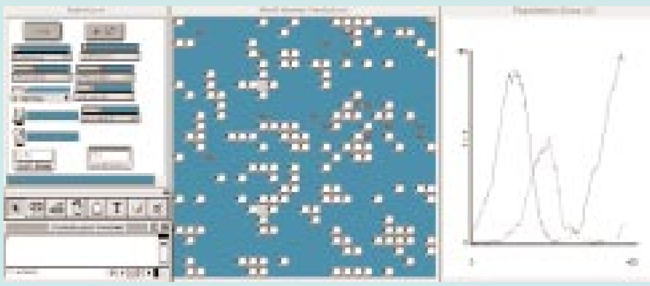

Figure 1: The StarLogoT window setup for the wolf-sheep predation model. In the upper left is the interface window that allows users to set model parameters and run simulations. In the middle is the StarLogoT graphics window which displays each individual wolf and sheep. On the right is a population plot window.

A dynamic graph of the population levels of sheep and wolves can be viewed alongside the screen. If the rule sets are chosen appropriately, a typical result is that the population graphs look like out-of-phase sine waves — sheep populations increase till the wolves have so much to eat that they increase, which reduces the population of sheep, which eventually, in turn, decreases the population of wolves, which results in an increase in the sheep population. (See Figure 2.)

This is a classical result, but seen here through the lens of emergent phenomena. The students control the behavior at the micro-level of the individuals and then observe the results at the macro-level of the populations. It is through experimenting with the dynamics of this connection that a powerful understanding of predator-prey dynamics can be achieved.

A second example is a model called Gas-in-a-Box, one of a suite of StarLogoT models in a package called GasLab. Gas-in-a-Box was originally created by a physics teacher, but the original model has been refined by dozens of students who have also created many variants and extensions of the original model.

The basic idea is a box containing thousands of gas molecules. Gas molecules are modeled as turtles that collide like elastic billiard balls, that is, they collide with the box and with other molecules without loss of energy. The user can set the mass and speed of any molecule. (See Figures 3 and 4.) The display color-codes the molecules, blue for slow, green for average speed, and red for fast.

In a typical first use, students initialize the molecules with equal masses and equal speeds but with random positions and headings. Thus all molecules start out green. When students run the model, they are usually surprised to see that the molecules turn color quite quickly and that many more of them turn blue than turn green. In other words, more of the particles slow down than speed up. Although this result is a direct consequence of a known

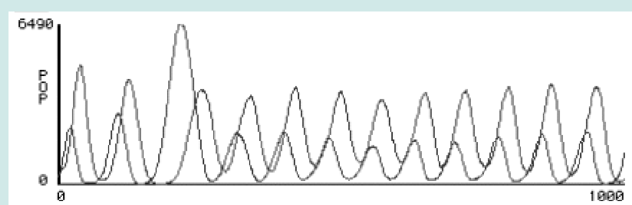

Figure 2. A typical population graph from a student rule-set. One line represents the size of the predator population, while the other represents the size of the prey population.

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StarLogoT—www.ccl.tufts.edu/cm/starlogoT

Gas Lab—ccl.tufts.edu/cm/models/gaslab.html s Lesson

arLogoT

/ilensky

law of gases, the Maxwell-Boltzmann distribution of molecular speeds, taught in high school physics, it is not recognized by students in this form. (In our experience, not just students, but even physicists are often surprised by this result.) Again, the key insight here is that the Gas-in-a-Box model allows students to see the gas from an emergent perspective. They come to see the connection between the micro-level of billiard ball collisions and the macro-level of the general characteristics of the gas as an ensemble. These two levels of description are typically taught separately in the high school curriculum. However, it is in understanding the connection between these two levels, how one emerges from the other, that leads to a powerful understanding of statistical thermal physics. The connection has been thought to be too hard for high school students, as it usually involves advanced mathematical machinery. But, through the use of multi-agent modeling languages such as StarLogoT, these ideas can be accessible to high school learners.

StarLogoT is in use by many students and teachers. In its years of use, we have assembled a large collection of "extensible" models (collectively entitled "Connected Models"). The sample models are drawn from a wide range of disciplines including physics, biology, mathematics, computer science, chemistry, materials science, ecology and economics. These sample models are created by students, teachers and researchers and go through a process of checkout and refinement before becoming a part of the distribution archive.

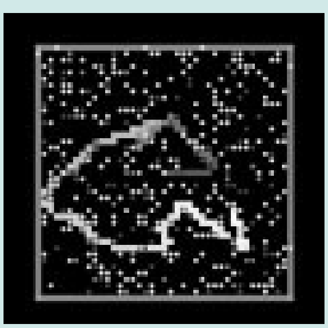

Figure 3. Gas molecules in a box. In a full color StarLogoT, fast particles appear in red, mid-speed in green, and slow particles in blue. The zig-zag line, which is yellow, traces the movement of a single particle.

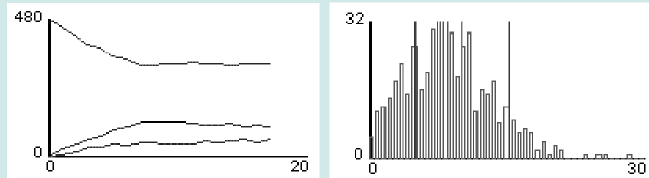

Figure 4. StarLogoT displays "live" plots and histograms of the molecules in the graphics window. 9a.(left) Plot of number of medium, slow and fast particles (top to bottom). 9b. Histogram of particle speeds.

In the classroom, StarLogoT is typically used in roughly five phases:

A) In the first phase, the teacher typically leads the students in off-computer activities (known as participatory simulations or emergent activities) that provoke thinking about emergent phenomena. In these activities, students typically enact the role of individual elements of a system and then discuss amongst themselves what global patterns they detect and how those patterns could arise from their individual behaviors.

B) In the second phase, the teacher presents a "seed" model (a simple starting model) to the whole class, projected through an LCD panel so that everyone can view it. The teacher engages the class in discussion as to what is going on. Why are they observing that particular behavior? How would it be different if model parameters were changed? Is this a good model of the phenomenon it is meant to simulate?

C) In the third phase, students run the model (either singly or in small groups) on individual computers and explore the parameter space of the model.

D) In the fourth phase, each modeler (or group) proposes an extension to the model and implements that extension in the StarLogoT language. Modelers starting with GasLab, for example, might try to add to the model by building a pressure gauge, a piston, a gravity mecha-

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Connected Models—www.ccl.tufts.edu/cm/models

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nism, or heating/cooling plates. The extended models are added to the project's library of extensible models and made available for others to work with as "seed" models.

E) In the final phase, students are asked to propose a phenomenon and build a model of it from scratch using the StarLogoT modeling primitives.

There are other simulation software packages that enable students to engage in phases B and C. However, because the students can't inspect or modify what happens inside these simulations, they can't engage in phases D and E and thus go more deeply into understanding the models. This is the problem with "black box" tools: they are easier to use at first, but provide fewer opportunities for learning. Other simulation packages, notably STELLA, are "glass box" like StarLogoT, but they ask students to model only at the level of populations. By enabling students to model at the level of individuals, StarLogoT makes it easier for students to begin modeling because they start at the level of individual behavior. Hence they can base their models on their own experience — both as *individuals* and of *individual objects* in the world.

We have worked with classrooms in all five of these phases. Generally, the depth of understanding of complex systems and emergent phenomena would be expected to increase as students start to more actively build, modify, and explore the models. The results that students can achieve with model extensions and designing their own models are often quite dramatic. Because of the great variations in available technology, learning time, and classroom organization, each phase has valuable applications.

Working in phase D, what we call the "extensible modeling" approach, allows learners to dive right into the model content. Learners typically start by exploring the model at the level of domain content. When they are puzzled by an outcome of the model, they design an extension to the basic model. This extension usually requires only a few language primitives to implement. This allows learners to follow a gently sloping path towards full StarLogoT language mastery — skill with the general-purpose modeling language is acquired gradually as they seek to explain their experiments and extend the capabilities of the model.

Conclusion

The inclusion of a complex systems perspective in school curriculum has many benefits for learners:

- ❖ We live in an increasingly interconnected world. Smokestacks in the Midwest cause acid rain in the East. Rainforest destruction in South America leads to greenhouse effects and weather pattern changes in Africa. Market collapses in the Far East can have great consequences on economies in the West. Traditional science which studies phenomena in isolation is not equipped to analyze and understand such systemic effects. Informed citizens in such a highly interacting world need tools that can help them cope with these complexities.
- ❖ Though there is increased desire for interdisciplinary learning, students studying in a traditional curricular framework find it difficult to see the connections between different domains of knowledge. One strength of the complex systems theory perspective is that it enables us to see common patterns across traditionally separate fields: physical matter is the emergent result of molecular interactions; ecologies and biological niches are emergent results of interacting organisms; economies and markets are emergent results of the interactions of buyers and sellers.
- ❖ Many everyday phenomena and experiences arise from the interactions of many different factors. Because these have been hard to study using traditional methods, they are excluded from the curriculum. Introducing complex systems allows students' personal experiences to be included in the curriculum – thus students see science as more personally relevant.
- ❖ An understanding of patterns as emergent phenomena, rather than as results of equations, is both a more accurate picture of nature and easier for most people to understand. Science becomes more accessible as a result of this change in viewpoint.

By introducing a perspective of complexity and emergent phenomena, we make science more accurate, more inclusive and more accessible to the great majority of students. @

Uri Wilensky is Director of the Center for Connected Learning and Computer-Based Modeling at Tufts University.
oas@ccl.tufts.edu

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StarLogoT—www.ccl.tufts.edu/cm/starlogoT

Designing Complex Models

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designed (see Winter '98 @CONCORD). It offers students a multi-level view of genetics and enables them to move easily between the levels. Clicking on an organism with the chromosome tool, for instance, will bring up the textbook view of the organism's chromosomes, represented as short, fat rectangles like popsicle sticks with lines across them representing the loci of various genes. The labels on these genes are in the form of popups that enable a student to change a gene, for example, from its dominant to its recessive form. When they do this, the organism that "owns" the genes changes too — its phenotype changes to reflect its genotype.

Obviously, in reality no one can alter a gene from one allele to another, nor would such a change, if it were possible, have any effect on the organism from which the gene came. Thus, the operation of changing genes in no way simulates a laboratory or clinical procedure. The affordance is included in the software in order to allow students to discover Mendel's laws of inheritance for themselves by observing their consequences in a direct and motivating manner. This phase of exploration by direct manipulation of genes usually lasts two or three days, after which the power to change, and even to observe genes directly is taken away and the students are forced to make inferences about genotype from phenotypic and breeding data, just as real geneticists do. Thus, by a carefully sequenced set of moves that progressively limit students' interactions with the software until they are similar to those available in the real world, we guide them bit by bit to reason in ways analogous to those of the professional scientist.

Evaluation for redesign

It is not enough to design a model for teaching — one must observe it in use, evaluate its effects, and modify it as required. Moreover, students are not simple, predictable robots. They do not bring identical attitudes and preconceptions to the learning process, and what they learn from working with an interactive model may differ, often dramatically, from what its designer intended. When this happens it may suggest the need for substantial redesign of the model and/or its accompanying pedagogy.

The management of inquiry-based classrooms, in fact, poses problems unrelated to the use of CBMs. Open-ended exploration that enables students to "construct their own knowledge" is a powerful teaching tool, but in practice it can be a very inefficient process, as students perseverate on a misconception, or "play around" for a significant fraction of the class time without making visible progress. It's all right — some might argue that it's essential — for students to struggle in this way, but if it goes on too long, they will become frustrated and turn off. Ideally, a tool for open-ended inquiry should help the teacher to intervene at just the right moment.

Moreover, the designer of a CBM must bear in mind that, just as teachers have different teaching styles, students have very different learning styles. In some situations it may be appropriate to let the student loose to explore a model with little or no direction, but at other times a more structured and linear approach may be called for. What is needed is a way to script how the software interacts with the student.

Scripts are not a new technology. Most business applications are scriptable, allowing one to write simple programs that will cause them to perform a specified sequence of often used functions with a single mouse click. In an educational context, scripts can display information to the student in the form of text, animations, audio, or video material. They can also gather information from the student, in the form of text entry or mouse clicks, and to receive updates from the CBM itself. Thus, they can monitor the students' actions. By constraining the problem very precisely, a curriculum developer can use this monitoring capability to identify "teachable moments" and can tell the script to intervene when such opportunities present themselves.

Linking models to the real world

Models, by definition, are not real and it is not always obvious how they connect to the real things that they represent. The most carefully crafted computer model, designed to teach important scientific concepts, may come across to students as just another videogame. When this happens what they derive from the computer may not go deeper than the skill required to "win" the game. In particular, it may not extend to reasoning about real-world phenomena or processes. Moreover, many scientific discoveries carry with them important implications for society. Consider, for example, the legal, ethical and moral dilemmas that seem to arise almost daily from scientific advances in genetics. In a world increasingly confronted with such issues it is unacceptable to teach science without encouraging students to consider its social implications, and this requires that one make explicit the

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Mendel—www-hpcc.astro.washington.edu/mirrors/MendelWeb

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Designing Complex Models

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links between the model and the real world.

Conclusion

Models, whether on or off the computer, aren't "almost as good as the real thing" — they are fundamentally different from the real thing. From an educational standpoint, they are neither better nor worse than "hands on" methods — the two approaches are complementary, and neither works very well in isolation. We have concentrated in this article on a particular kind of computerized model — the computer-based manipulative — as an example of one way to use computers to teach science. We have examined the design of CBMs with particular attention to such issues as selective intervention, sequencing of problems, and linking activities on the computer to real world analogs. The CBM paradigm, powerful though it may be, must be brought to bear in the context of conjunction with many other tools — "wet" labs, textbooks, classroom activities — that can help students to link the various features of the CBM to the real world facts, phenomena, and procedures that they represent.

The most important question that still confronts us in the use of CBMs is "what are the students learning?" In careful experiments, repeated in many classrooms, we have observed striking discrepancies between students' performance on the computer, captured in observation notes and on videotape, and their scores on written tests. We do not lay the "blame" for this discrepancy on the tests themselves, which have been designed to assess what we think the students are learning. Rather, it appears that learning accomplished entirely within the context of interactions with a CBM may become learning about that CBM, rather than generalizing to learning about the domain. It is very important, therefore, to broaden the learning process so that students are made explicitly aware of the model underlying the CBM, and of its application to real world phenomena. This broadening process has implications for the teacher, the curriculum developer, and the software designer.

We hope that the scripts that we are currently designing for BioLogica (see Spring '98 @CONCORD) will help to make students conscious of what they are learning when they explore and solve problems on the computer, and how what they are learning applies in the broader world outside the classroom. @

Paul Horwitz is senior scientist for the GenScope and BioLogica projects.
paul@concord.org
This article is excerpted from the forthcoming book Modeling and Simulation in Science and Mathematics Education, *published by Springer-Verlag.*

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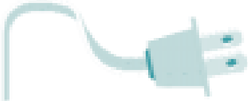

INTEC Unplugged: A true story of inquiry

by Patricia Goodnight

Patricia Goodnight, a biology teacher in Washington, D.C., describes her experiences with INTEC, a yearlong netcourse for math and science secondary teachers, developed by The Concord Consortium and funded by the National Science Foundation (NSF). INTEC engaged over 800 participants across the country and around the globe. Participants learned new tools and technologies as they developed their skills at using inquiry as an instructional approach in their own classrooms. For many participants, the netcourse itself was inquiry in action.

INTEC, the International Netcourse Teacher Enhancement Coalition, is now compiling the stories of participants, including Goodnight's, in a book on inquiry, to be published in spring 2000.

When I read the overview of the INTEC netcourse as well as instructions for accessing the web site, I promptly wondered aloud why I had ever signed up for the INTEC course. I felt as if I were beginning a long journey through a very dark tunnel. Even after reading the introductory information, I had no idea what to expect: this was my first online course.

I proceeded on my virtual journey while sitting in my basement with a computer. At least there was no dress code and it didn't matter what time of day or night I did my work. The course schedule and assignments were explicit; there was a timeline – with some built-in flexibility – and, of course, deadlines. But, if I needed help understanding the instructions or an assignment, a quick email to the project coordinator or the academic director would bring a response overnight.

The course began with an eye-opener: the first assignment was designed to make INTEC participants – teachers from across the country and in Canada, Russia, and Ireland – aware of the importance of teaching for conceptual understanding and how implementing the inquiry approach facilitates this level of understanding. I asked some of my students, each of whom was assigned a password, to respond online to several conceptual probes (questions) designed to get students to elaborate as much as possible on their answers, thereby enabling the teacher to determine the extent of the students' conceptual knowledge.

For example, students were asked to respond to the following: A container of bleach and ammonia is set up in two rooms with a lab assistant in each room. Which vapor would be detected first, and why?

Invariably, the students indicated that the ammonia would be detected first because it is "stronger."

This was their "private universe": the definitions and explanations by which they make sense of their world. This was an epiphany for me: the first glimmer of light on the far side of the INTEC tunnel.

As I thought about my students' responses, I learned a lot about my style of teaching and how I needed to make some changes in the way I designed my lessons. I would have to restructure them in order to get students to a point where they could demonstrate conceptual knowledge.

For instance, I realized biology can't be taught as a separate entity anymore. A way and time must be found to incorporate chemistry and mathematics. More work for me!

With the gentle prodding from a mathematics colleague, I selected the Calculator Based Laboratory (CBL) module to use for the second half of the course. My colleague was familiar with CBL and thought that if we chose the same practicum, we would have an opportunity to work together as a team. Since I teach biology, it would have been logical for me to select another progarm, such as BioQUEST or GenScope or even Algebra. Any one of the three seemed doable. But my colleague assured me that she would assist me whenever the need arose. I acquiesced – with much trepidation.

When the equipment arrived, I looked at it and wondered, once again, what I had gotten myself into. The light that had briefly shone when doing the conceptual probes had dimmed significantly.

It comes as no surprise that teachers are always busy. Thus began my frustration. I was getting behind with INTEC coursework. While other

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INTEC—intec.concord.org BioQUEST—bioquest.org CBL—www.ti.com/calc/docs/cbl.htm
National Science Education Standards—www.nap.edu/readingroom/books/nses/html/6a.html NSF—www.nsf.gov

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INTECers were posting their successes – and, admittedly, their own problems – I still had no idea what to even do with the equipment.

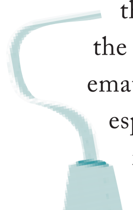
Finally, I learned how to set up and use the CBL. Some time later, I felt confident about involving my students in an activity.

I planned and implemented the "Use of Sonic Ranger and CBL to Test Hypotheses" activity from the "New Standards High School Science Portfolio: Scientific Tools, Techniques, and Communication Exhibit." With this introductory exercise, I wanted to demonstrate that the CBL provides a link between science and mathematics. Pairs of students learn how to set up the equipment to test their hypotheses regarding the motion required to produce a specific line on the calculator.

The motion detector is a sonar device that emits pulses which are reflected back to it when they reverberate from an object at a distance. The procedure called for the students to draw a line and then write a description of how one has to walk in front of the motion detector to produce this line. Prior to testing the hypothesis, each pair of students had to reach consensus on the hypothesis regarding the type of line that would be produced based on the movement in front of the motion detector. The students had to assemble the equipment, access the correct program which was in the calculator, and include the values for y-minimum and y-maximum. Once they accomplished this, students tested their hypotheses by walking in a prescribed manner. They then determined whether the actual motion in front of the detector produced the same line that was drawn originally.

This inquiry-oriented activity allowed for creativity and discovery. The CBL permits more time to analyze data as opposed to plotting it. Actual distance-time data are generated. The interesting question then becomes "What does this mean?" I observed students thinking logically and asking a lot of "What if" statements. They were developing an understanding about negative and positive slope.

I enlisted the help of other mathematics teachers in my attempt to learn this technology. Thanks to the patience of several mathematics teachers and especially the math department chair, I succeeded.



Students at all grade levels and in every domain of science should have the opportunity to use **scientific inquiry** and develop the ability to think and act in ways associated with inquiry, including asking questions, planning and conducting investigations, using appropriate tools and techniques to gather data, **thinking critically** and logically about relationships between evidence and explanations, constructing and analyzing alternative explanations, and communicating scientific arguments.

National Science Education Standards

CBL became a sort of buzzword at our school.

At times, we practiced our CBL activities in the hall. The curiosity of other colleagues was aroused as they walked by. As a matter of fact, during a PTA meeting when there was a lull, we seized the moment by setting up the experiment which required temperature probes. We wanted to investigate Newton's Law of Cooling. We assembled our materials and proceeded to collect data. It was refreshing to be part of a group of mathematics and science teachers working together for the common interest of students.

The INTEC experience was a departure from the mundane "sit and git" type of course that's filled with theoretical jargon about education that is frequently completely devoid of practical application. From the beginning, I involved my students. I felt as if I had a learning laboratory – an inquiry lab, one might say.

The students were learning a technology that was new to them. And I went from knowing nothing about CBL to being a quasi-expert on the technology. I'm now a convert to how valuable this technology is for our students. I saw firsthand how the CBL allows for the integration of the inquiry approach – guided or open-ended – and how students ask more questions, form and test explanations, and use critical thinking skills.

As I reflect on my INTEC experience, I can say that it included an epiphany or two and, of course, the trials and tribulations one expects, though doesn't necessarily prepare for, in life. @

Patricia Goodnight teaches biology at Bell Multicultural High School in Washington, D.C.

LINKS ON THIS PAGE
CBL—www.ti.com/calc/docs/cbl.htm
INTEC—intec.concord.org
Bell Multicultural High School—www.incacorp.com/bmhs

Perspective

What Bell Curve?

by Paul Horwitz

“Rather than teaching them facts, the computer was changing the way they thought.”

Luc learned Einstein’s Theory of Relativity at Boston High School by building computer “thought experiments” that simulate objects moving at close to the speed of light. They observe these in one frame of reference and try to imagine what they would look like in another – out the window of a moving train, for instance.

Some people claim that human intelligence is largely determined by DNA. Education, they imply, is irrelevant. Luc and his friends are quietly proving them wrong.

I observed some students for several months as part of a National Science Foundation project that explored the use of computers for teaching math and science. Most of the time they worked in small groups building pictures in their heads, using the computer to transform them into live, interactive demonstrations. Every so often they seemed to breach some mental barrier reef and surface sputtering, clinging proudly to a new idea. Their smiles at these times clutch at the heart. They do not smile in school very often, these inner-city kids.

These introductory physics students – all but one Haitian or African American – had advanced steadily from simple problems to the notoriously difficult Twin Paradox, according to which someone who embarks on a round trip at high speed returns younger than her twin sister. They had followed the same path, encountered the same frustrations, and overcome the same obstacles as any students I have observed – and they had progressed at about the same rate.

Nevertheless, nearly every member of the class showed signs of severe educational deprivation – particularly in mathematics. Their knowledge of the decimal system was spotty, they were easily confused by numbers over one million, and they had difficulty understanding simple graphs. It is hardly surprising that they performed poorly on the tests society uses to evaluate them.

Years of neglect have left these students perilously at risk, but modern technology, combined with a new approach to learning, is having a remarkable effect on them. Rather than teaching them facts, the computer was changing the way they thought. It provided them with a manipulable, visual medium within which they could construct scenarios, puzzle over them, and alter them to answer “what if” questions. It freed them up to think without having to calculate, build without having to describe, plan without having to formalize. It rewarded “street smarts” over “book learning.”

It is comfortable to believe that something as complex as mental ability could be reduced to a neat set of numbers. It appeals to our national preoccupation with quantifiable statistics while excusing our failure to educate a vast and growing number of our youth. But perhaps its most important function has been to insulate us from what might otherwise become the intolerable suspicion that in ceasing to believe that all men and women are created equal we have placed at risk the very foundation of our democracy.

One day I asked Luc, who had recently been informed that low SAT scores might destroy his chance for higher education, why he liked the Relativity class. He thought for a moment, then looked up at me with a shy smile. “I like it because we are doing things that most college students cannot do.”

“How does that make you feel?” I asked.

“It makes me feel intelligent.”

The confidence and self-esteem engendered by his success in this class may not prove sufficient for Luc to overcome the formidable obstacles he will face on the way to becoming a productive citizen in a knowledge-based economy.

But it’s a start. @

Paul Horwitz is senior scientist for the GenScope and BioLogica projects. Reprinted with permission from NSTA Publications.

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GenScope Breeds BioLogica

Our successful GenScope project for teaching genetics to high school students is complete and we are now working on its successor – BioLogica™, a manipulable model of biological processes. GenScope provides teachers and learners with a tool that enables students to investigate scientific and mathematical concepts through direct manipulation and experimentation. Students and teachers can manipulate the processes of inheritance on six different, but related, levels: DNA, chromosome, cell, organism, pedigree, and population. This allows students not only to read about genetics, but actually observe and manipulate processes at one biological level that affect life at another. You can download a free copy of GenScope from our web site.

BioLogica differs from GenScope in being scriptable, which enables us to set up a sequence of puzzles, and then interact with students as they attempt to solve them. BioLogica runs on Mac, PC, and Linux machines. For more information about BioLogica, contact Paul Horwitz (paul@concord.org). Both projects are supported by the National Science Foundation.

http://genscope.concord.org

Beacon Award Nomination

Concord Consortium's Teacher Learning Conference™ (TLC) course, which prepares high school teachers to offer netcourses through the Virtual High School®, has been nominated for Lotus Development Corporation's Beacon Award, given in recognition of those Lotus Business Partners who have excelled in leading the Lotus industry by providing expert and quality products, solutions and services to customers. Year 2000 awards are given to services and solutions built around Lotus' key technologies. Judged by a combination of leading industry press and analysts worldwide and Lotus executives, the Beacon Award winners will be announced in January during Lotusphere 2000 in Orlando, Florida.

http://www.emea.lotus.com/partners/usbeacon.nsf/bapages/bacategories

Handheld Design Awards Announcement

Winners of the Center for Innovative Learning Technologies (CILT) Handheld Design Award Competition will be announced on March 6. New, original educational applications of Palm technology will be judged using four criteria in six categories. The Exploratorium Science Center in San Francisco will host the awards ceremony through a live webcast.

http://kn.cilt.org/palm99

MOOM Beams

Read indepth about "Moving Out of the Middle" (MOOM), Concord Consortium's popular class for online moderation of courses, in the December 7, 1999, issue of WebCT Newsletter — look for "Industry Watch." The article explains the pitfals that online moderators can fall into as well as principles of good moderation. For anyone thinking of taking the MOOM class (see page 12 of this issue of @CONCORD), the WEBCT article includes many comments from MOOM participants . According to WebCT, their article on MOOM received the greatest number of hits within the first 24 hours of any article ever on their site.

http://www.webct.com

The Concord Consortium
37 Thoreau Street
Concord, MA 01742
PHONE 978.369.4367
FAX 978.371.0696