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ABSTRACT

Recent technological advances and new software packages put unprecedented power for experimenting and theory-building in the hands of students at all levels. Microcomputer-based laboratory (MBL) and model-solving tools illustrate the educational potential of the technology. These tools include modeling software and three MBL packages (which are described in this paper): (1) The Bank Street Laboratory, a large hardware, print, and software package which enables students to perform a wide variety of experiments involving light, temperature, and sound; (2) Exploring Heat, an MBL unit developed with special attention to the needs of mildly learning disabled late elementary school students; and (3) Experiments in Chemistry, a secondary/college-level package for recording, graphing, and analyzing pH, electromotive force, and temperature data. MBL and dynamic modeling software are important to science education because they complement each other. In addition, students do science, activities become more student-centered, and software has applicability to many grade levels. Extensive in-class testing shows that the desirable characteristics for the successful educational use of both MBL and dynamic modeling software include ease of use, fast feedback, the computer's computational ability, and use of graphical output. (JN)

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MODELING AND MBL:

SOFTWARE TOOLS FOR SCIENCE

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ABSTRACT

Recent technological advances and new software packages put unprecedented power for experimenting and theory building in the hands of students at all levels. Microcomputer-based laboratory and model solving tools illustrate the educational potential of the technology. Properly used, these approaches can revolutionize mathematics and science instruction, but only when teachers have the technical background and teaching styles to exploit the full potential of the technology.

SOME NEW TOOLS

Microcomputer-Based Laboratories

The educational use of personal computers in the laboratory to gather, analyze, display, and store data, a class of application we have named microcomputer-based labs (MBL), has only recently begun to gain widespread acceptance. Recently, a number of new MBL products have been introduced (Tinker 84,85) designed for grades 4 through college and for the home educational market. In addition, a number of funded projects are underway that focus on developing new MBL applications, researching their effectiveness, and disseminating MBL techniques. For instance, the MBL Project at TERC is a five-year NSF-funded project that will develop a wide assortment of new MBL materials using low cost computers, interfaces, and probes. All this activity indicates that additional and better MBL material will become available in the near future.

Three relatively new MBL packages developed at TERC illustrate the educational potential of the approach: The Bank Street Laboratory (CBS/Holt, Rheinhart, and Winston), Exploring Heat (DCH Software), and Experiments in Chemistry (HRM Software).

<u>The Bank Street Laboratory</u> is a large hardware, print, and software package that is part of the Voyage of the Mimi Project at Bank Street College of Education. The project has produced material for an entire year of mathematics and science instruction at the 4-6 grade level coordinated with a 13-episode video program aired nationally on public television. The

Bank Street Laboratory enables students to perform a wide variety of experiments involving light, temperature, and sound. One of the many possible measurements--Sound Print--illustrates the sophistication of the package.

Sound Print captures one second of sound and displays the compressed waveform and a representation of the strength of frequencies present in the waveform. Figure 1 illustrates output obtained from a whistled tune. The form of the resulting display closely resembles that used to display whale sound prints used by characters in the TV show. The show enhances the implication that students can participate in the same type of scientific enterprise that was performed by characters with whom students can identify who were pursuing humane goals (saving whales).

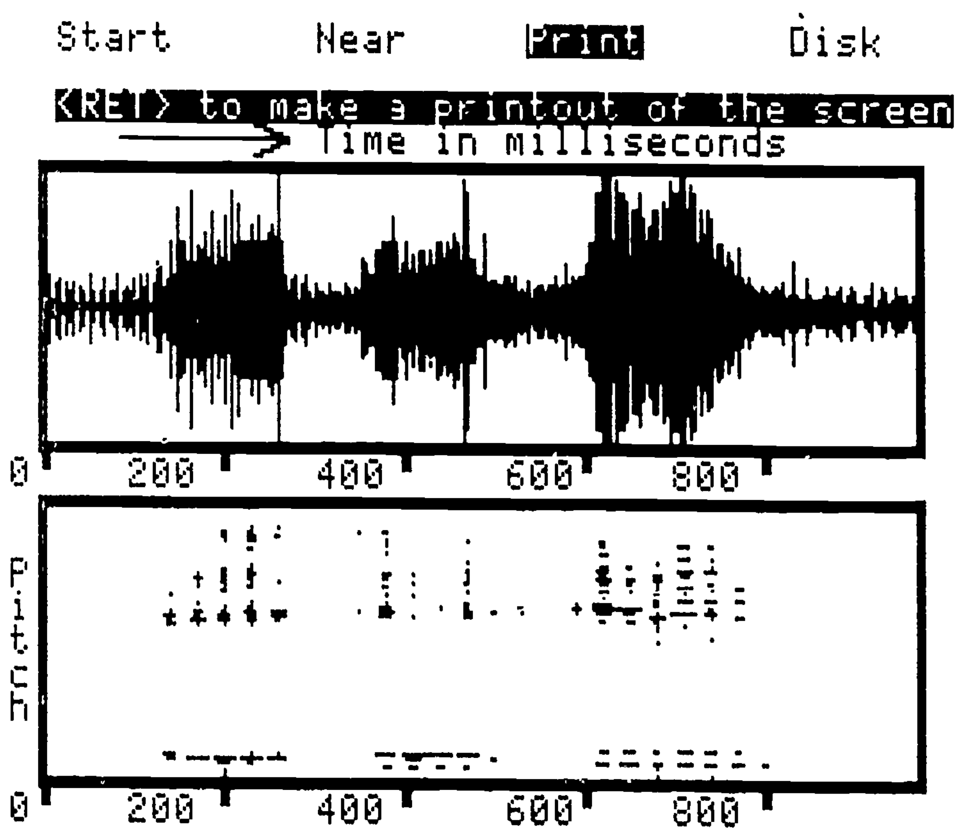

Figure 1

Technically, Sound Print is quite sophisticated. A microphone is sampled every 112 microseconds, generating 8K points. These are transformed in ten seconds in groups of 256 points using a fast Fourier transform assisted by a hardware multiplier. Students have no more idea that all this is happening than they know of the inner workings of their TV or telephone system. All that matters is the relation of input to output. Students learn that whistles give single lines that go up and down with pitch, that other sounds, such as the vowel "e" in Figure 1, give characteristic patterns that are somewhat independent of pitch. They can attempt speech recognition visually, and learn to appreciate the sophistication of animal audition.

Exploring Heat is an MBL unit developed with special attention to the needs of mildly learning disabled (LD) late elementary school students. The adaptation of temperature graphing software to the needs of LD students involved careful attention to screen layout, the user interface, and other features of the student-computer interaction. The resulting software had as great a capacity for data acquisition and scientific investigations as earlier software not designed for LD students. The same features that make it usable by LD students make it easily used by all students and, therefore, an ideal tool for mainstreamed classrooms.

One of the innovative aspects of Exploring Heat is its use of a representation of kinetic molecular theory. At certain points within the program, a box on the screen shows an animated simulation of the atoms measured by the probe, as illustrated in Figure 2. The speed and type of movement of the "atoms" in the box changes as the temperature sensed by the probe changes. In this way the mental "hooks" provided by this kind of model are available to LD students with a minimum of words and verbal descriptions.

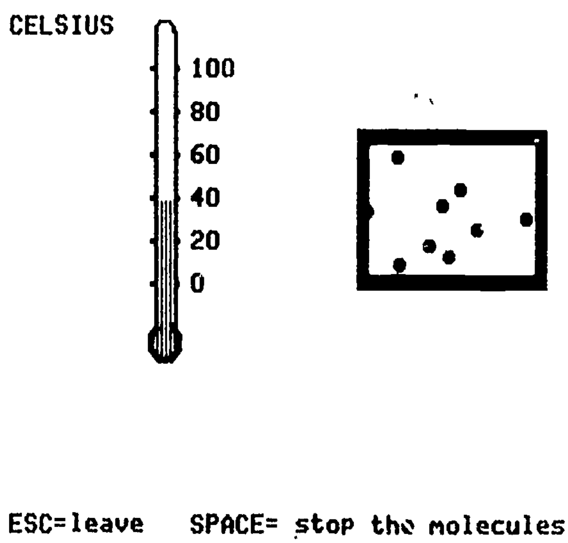

Figure 2

The material was carefully tested in public school classrooms containing mainstreamed LD students. There was no significant difference between the performance of LD and other students on the material. This is explained by noting that LD students represent a normal distribution of intelligence. It seems that the MBL package was able to bypass the communication difficulties experienced by LD students. For several students their understanding of the material was important psychologically, giving them a rare positive learning experience from which they could gain confidence.

<u>Experiments in Chemistry</u> is designed for advanced high school and college general chemistry courses. A single integrated program provides the ability to record, graph, and analyze pH, EMF, and temperature data. Compared to other MBL packages, its data display and analysis functions are unusually strong. Figure 3 illustrates this capacity with pH data from a titration displayed whole, expanded around one equivalence point, and then differentiated once and twice. The package also provides two independent screens and allows data to be fit over selected parts of the range to best fit straight lines.

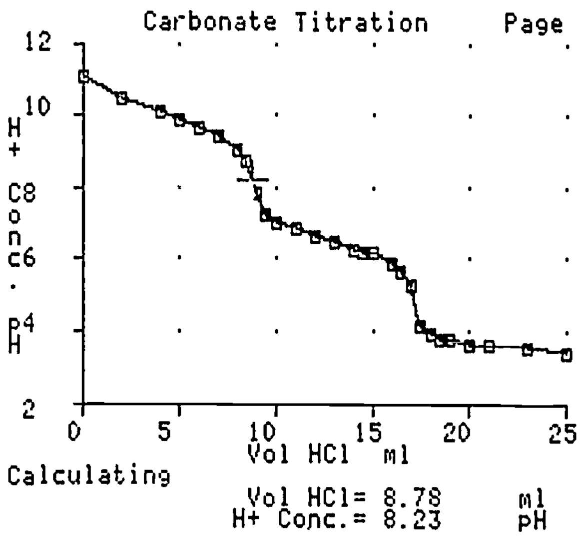

Figure 3a

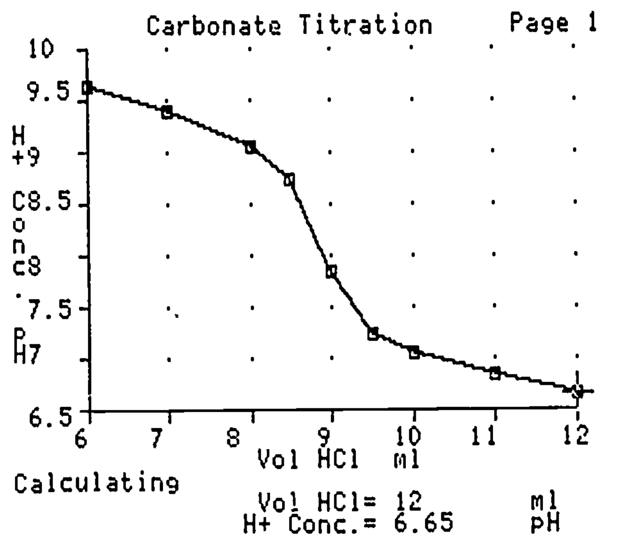

Figure 3b

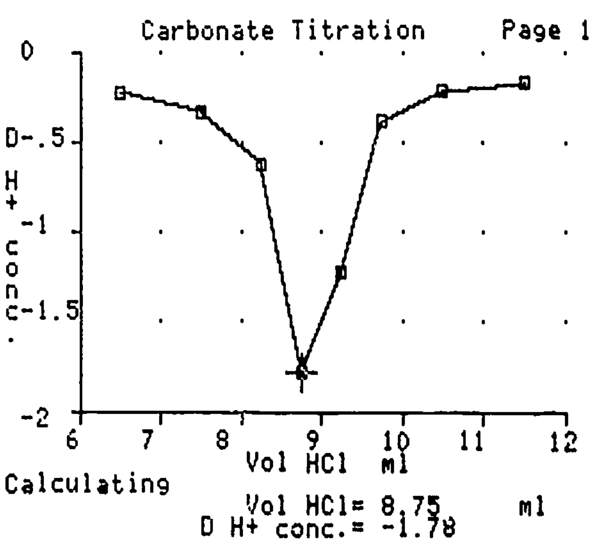

Figure 3c

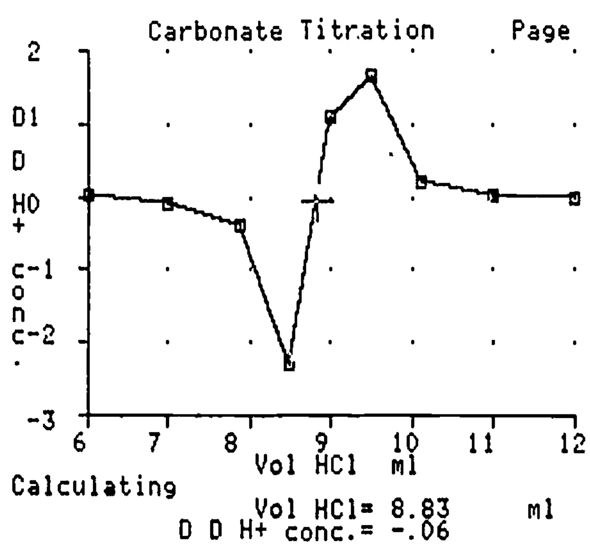

Figure 3d

Modeling Software

Software can be used for exploring models of the real world in many ways. The class of modeling software treated in this paper is the large subset of the modeling universe concerned with dynamic models, models of systems that change over time. The application of computer models to complex systems has spawned the field of systems dynamics and has had major applications in business and many academic fields.

The best use of models has students create the model rather than simply explore a simulation, a canned model that someone else has created. While simulations based on models others have created have an important role in learning about science, the ability to create a model seems much more central to the goals of science education. Creating a model is a form of theory building, and testing the accuracy of a model goes to the essence of science.

The use of dynamic models in teaching was popularized by Richard Feynman in his historic introductory physics lectures at UCLA (Feynman 63). Subsequently, numerical solutions in mechanics, and to a lesser extent, in other physics topics, have become an accepted part of introductory university physics instruction. Dynamic models allow students without an understanding of calculus to gain insight into dynamic systems and give these students the ability to solve interesting, complex problems, even problems that do not admit to a closed analytical solution. However, these techniques have failed to gain wide acceptance in introductory courses in other disciplines and at the pre-college level.

Nancy Roberts has pioneered the use of dynamic models at the pre-college level. She has developed curriculum material (Roberts 81) and participated in the development of microDynamo (Addison-Wesley), a microcomputer version of Dynamo (Richardson 81), a mainframe systems modeling language widely used in academic applications. Professor Roberts has successfully taught students in grades 9-12 to create models for and to solve sophisticated systems using microDynamo. Although dynamic systems are based on calculus, these students required no more than the usual mathematics taught in a first course in algebra. These results are all the more remarkable because microDynamo has the strong stamp of its mainframe roots; it is card-oriented, results are not available until the entire model is calculated, and it is slow.

The interactive graphics, sophisticated user interface, speed and computational power of more recent software running on MacIntosh-class computers offer exciting possibilities for better software for solving dynamic systems which could make dynamic modeling much more widely applicable in education. Stella (High Performance Systems) is an example of modeling software that begins to exploit these possibilities.

Dynamic models can be specified graphically, using icons that have been developed to represent elements of systems. The iconic representation is used as a way of thinking about systems that is accessible to students with modest command of mathematics. The critical calculus ideas of rate and change are incorporated into icons representing reservoirs and valves.

For example, Figure 4 illustrates a simple system of unrestrained population growth using conventional icons.

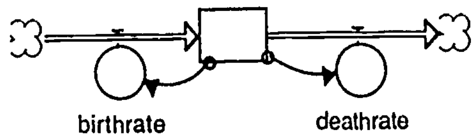

Figure 4

To solve a dynamic system, this iconic representation is usually translated into another representation for computer solution. The exciting possibility presented by modern personal computers is that this iconic representation could be the only input required, that the software could compute the system performance directly from the icon picture.

Stella is an example of a system solver that works directly from icons. Figure 4 is a model specification dumped from a Stella screen. By simply pointing to "RUN" on a pull-down menu, the solution shown in Figure 5

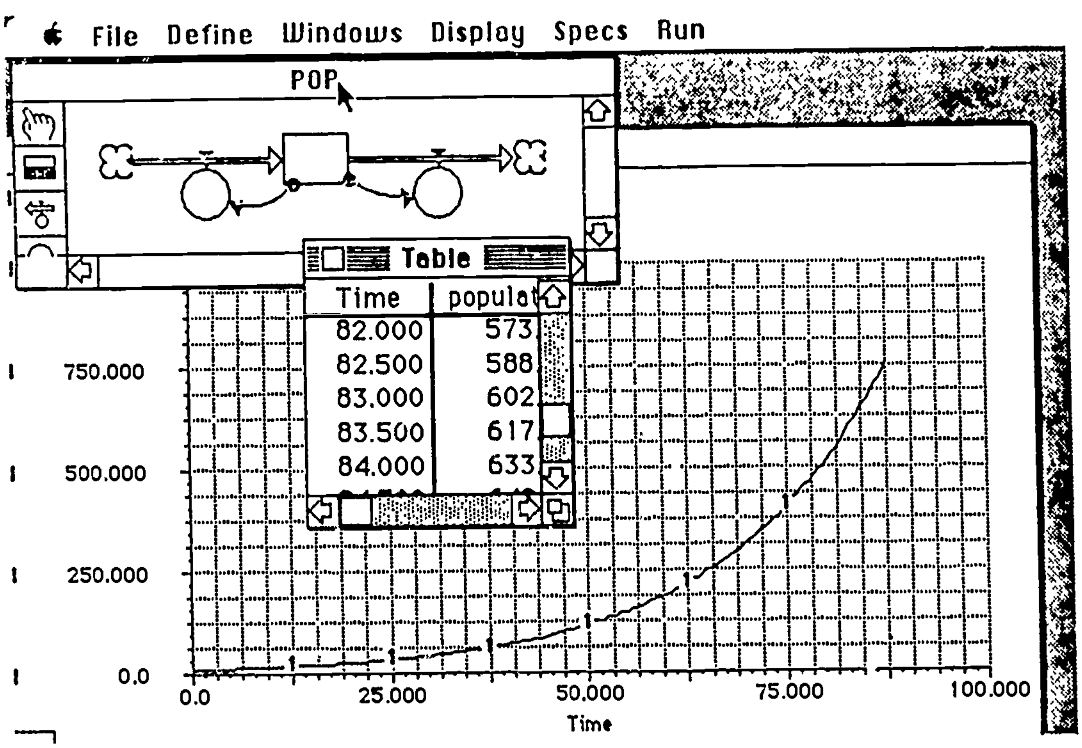

Figure 5

is generated for this system. The model can be created and changed graphically using the mouse. For instance, a few changes in the model to link high population with a decreased birth rate are easily incorporated and result in the model shown iconically with its solution in Figure 6. Not all the details of the model are evident in the picture; details of the assumed relation between population and birth rate are "inside" the birth rate circle, accessible to the user by clicking the mouse on the corresponding icon.

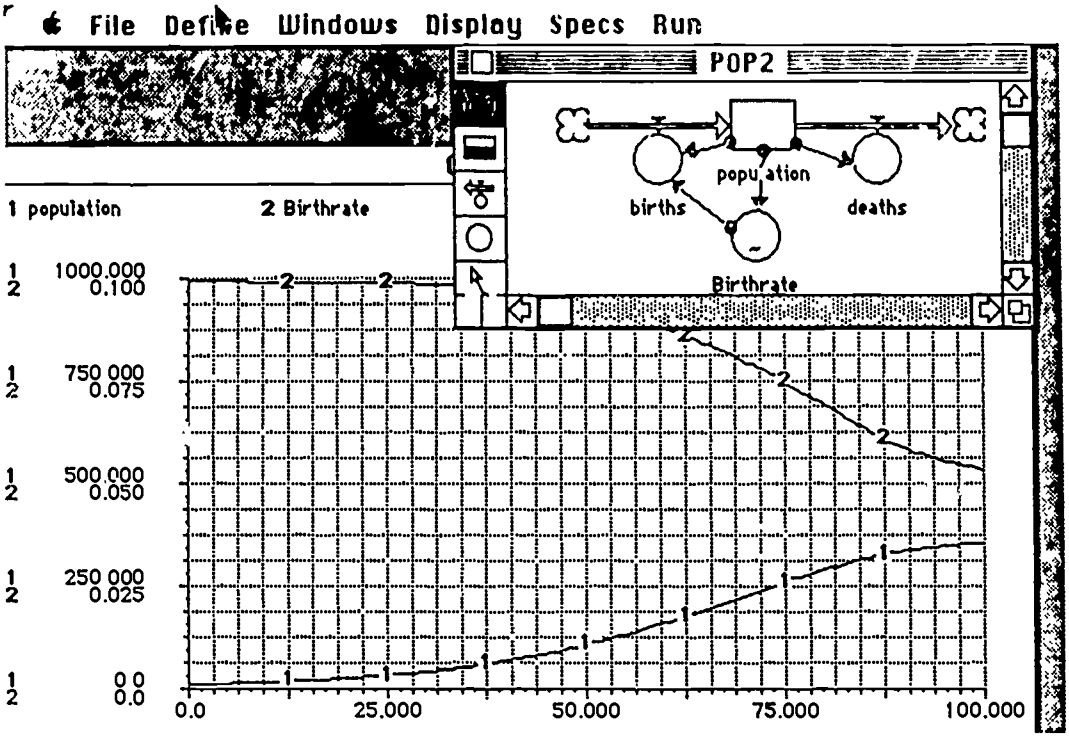

Figure 6a

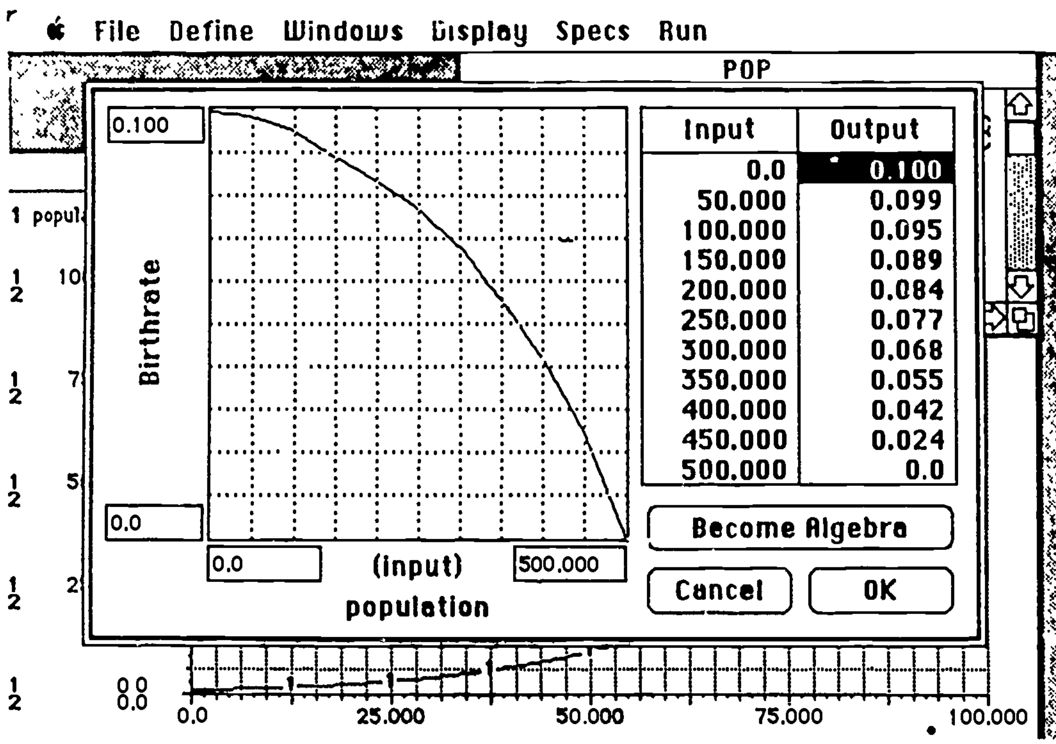

Figure 6b

While Stella is now a unique program, available only on the MacIntosh, it is the harbinger of a new class of modeling software that is easy to use, fast, and highly interactive. By combining iconic representations of complex systems with the interactive graphics now possible on personal computers, any student who can draw can begin solving systems. With this new technology, not only will calculus no longer be a prerequisite, but algebra will not be absolutely necessary.

Mary Budd Rowe (Rowe 84) has shown that students in early elementary grades can create plausible models of interacting systems in an iconic representation. This new technology could convert these students' models into quantitative predictions. Perhaps the ability to interpret graphs will emerge as the only traditional math prerequisite to a sophisticated understanding complex systems. Recent results indicate that MBL software may help facilitate graph interpretation and comprehension by students as early as the mid-elementary level. If this is the case, surprisingly young students will be able to undertake independent experimental and theoretical investigations given the combination of emerging MBL and modeling tools.

EDUCATIONAL ISSUES

MBL and Modeling Symbiosis

MBL and dynamic modeling software are important to science education because they complement each other. MBL enhances students' ability to experiment and model building enlarges their opportunities to theorize. Used together, students can alternate between gathering data and construction of theories that explain these data in a cycle that epitomizes the scientific method. While this has always been possible without computers in limited domains, the technology vastly expands the topics in which students can "do" science as opposed to learn about science. This expansion of the potential topics is important. Without these computational tools, topics students can address from both a theoretical and experimental perspective are often either contrived or mathematically taxing and often both. With the power of these technologies, interesting topics can be addressed even though instrumentation is required to obtain the data and the theory is based on advanced mathematics.

A nice example of the interplay of experiment and theory occurred inadvertently when the author recorded the motion of a pendulum using a game controller as pivot and transducer. Typical data are shown in the upper trace in Figure 7. Using a simple dynamic model to solve the standard textbook equation of motion for damped harmonic motion gives the solution shown in the lower trace of Figure 7. Terms that control the frequency and damping have been adjusted interactively to match the data as closely as possible. While the general shape of the curves agree, it is clear that the correspondence between theory and data could be better. The data show less friction than the model at first, and more later on. Of course, one's first instinct is to doubt the data. After all, the game controller is not designed for accuracy and its use may introduce systematic errors. After some time pursuing this tact, I was convinced that envelope of the data was accurate and unlikely to be affected by potential errors. This forces one to reexamine the model.

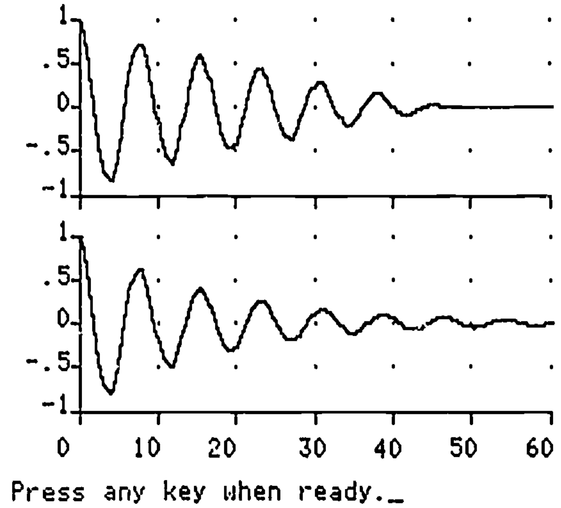

Figure 7

The problem is in the model of friction. The initial assumption of friction proportional to speed was unduly influenced by the textbook choice of an assumption that led to a solvable equation. A better assumption is that friction, F, is pure oppositional: a constant force, b, in the opposite direction of the velocity, v. Mathematically, this is

$$F = -b * ABS(v) / v$$

where ABS(v) is the absolute value function. This formula results in a non-analytic system of equations, so it is no wonder that this kind of friction is seldom covered in texts. To a dynamic model, however, one formula is as good as another. This friction term is easily entered and leads to the results shown in Figure 8, where experimental data are shown as boxes superimposed on the results of the model. The agreement between theory and experiment is remarkable.

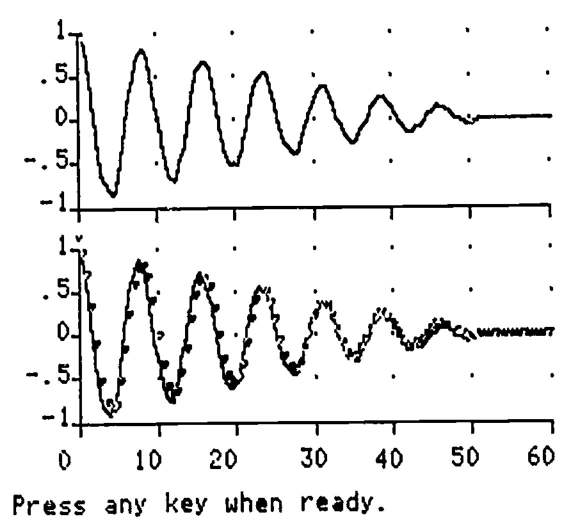

Figure 8

This anecdote illustrates how the recursive use of powerful MBL and modeling tools can work together to help one gain important but subtle knowledge about the natural world, in this case about the nature of friction. Used in tandem, it seems reasonable to predict that these tools will vastly expand the areas of science students can explore and learn.

Common Characteristics

Through extensive in-class student testing, we have developed a list of desirable characteristics for the successful educational use of MBL software, criteria that also appear to apply to modeling software.

Pure Tools. The best MBL software leaves all decisions about the use of the software to the user; it is a pure tool. Software of this sort is like a wrench it can be used for many purposes, it can even be used incorrectly; but there is nothing about the tool that makes any judgment about right or wrong.

Ease of Use. Great care must be taken in designing the user interface for powerful tool software. It is easy to include so many options that the beginning user is overwhelmed. The use of menus, default values, overlays, help screens and icons are all essential to making a large range of options accessible.

Fast Feedback. The time delay between a user's action and the manifestation of that action is a crucial variable in learning. A temperature graph should appear as an experiment is underway, not afterward; the effect of changing the damping in a mechanics model should instantly change the graph of the solution. Fast feedback is an aid to memory, it tightens the association between cause and effect, and it helps students sort out the effects of multiple variables.

Computation. Many MBL applications and most dynamic models involve prodigious amounts of computation. They take advantage of a computer's strength and make it available to students.

Graphical Output. Graphs seem to be comprehensible to a wide range of students when introduced in an MBL context. Graphs provide an alternate symbol system that summarize and communicate information about the affect of a single variable. Theoretical predictions and experimental data can easily be compared graphically, as illustrated in Figures 7 and 8. Thus, the graphical presentation of data and theory promise to be an important medium of communication about science, even for very young, LD, and dyslextic students.

Educational Significance

Doing Science. The most exciting possibility created by the powerful tools described here is that they enable students to be scientists, to participate fully in the adventure of science; to experience firsthand all the aspects of the scientific method from hypothesis generation through experiment design, to verification or rejection of the hypothesis. Student experience usually concentrates on data taking, giving a distorted idea of science.

The Locus of Authority. Tools that allow students to learn from natural phenomena shift the locus of authority away from the text and teacher. There is no reason to expect teachers to be able to predict or explain the results of many investigations students might undertake. While this is healthy, many teachers are uncomfortable with this and need help in adapting.

The Appropriate Grade. One of the most striking findings emerging from our work, is that well-designed tool software can be used by students across a very large range of grades. The Bank Street Laboratory, designed for grades 4-6, has been successfully used in high school and college. The same phenomena are of interest at all these levels, the differences are in the surrounding justifications and explanations. Similarly, modeling software tools seem likely to be useful at many levels.

This breadth of applicability has several salutary consequences. It implies that a few software/hardware packages will serve a large number of students. This results in economies for schools and encourages publishers to invest heavily in development, yielding unusually high-quality products.

The Calculator Argument. Many educators worry that the powerful tools described should not be used until students fully understand them. This is simply another manifestation of the discredited argument against the educational use of calculators. Of course, sometime, some advanced students should learn the theory of differential equations. But only a Luddite would deprive beginning students of technology that could help them learn important math and science concepts merely because they cannot explain how it works. If a similar criterion were applied to telephone users, few people would be allowed near phones.

Long-range Impact

The software discussed here has the potential of altering the conventional math and science curriculum. Numerical methods, exemplified by systems dynamics, are usually studied after calculus and differential equations. If students can create and test reasonable models based on rates of change without calculus, then numerical methods can precede calculus and even build students' intuition that can make subsequent calculus courses easier to understand. This reversal could vastly expand students' ability to solve applied problems that occur in science. This, in turn, would permit a broader range of topics to be studied quantitatively in science courses, particularly interdisciplinary and complex systems such as encountered ecology, the physics of athletics, chemical reactions, and demographics. In addition to broadening students' science background, these topics are more motivated and relevant than many stylized textbook topics.

The changes predicted will be implemented very slowly, not because of the cost of computers or the scarcity of software. The fundamental problem is that these changes will entail both a major upgrading of the content teachers are required to understand and a major change in the style of instruction. But the slow rate of change belies its inevitability. In the long run, the cheap, easily controlled computational power of computers will have to penetrate math and science education. Students, parents, employers, and national self-interest will demand it. Science teacher preparation and in-service programs, and college faculty development projects should take cognizance of these trends and begin offering MBL and numerical methods topics.

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DCH Software, Lexington, MA

High Performance Systems

HRM Software

Captions:

Figure 1. A screen illustrating sound waveform analysis. The upper trace is a compressed waveform captured during three repetitions of the vowel "e" at different pitches. The lower trace is the sound print of frequency vrs. time. The frequency scale is linear from 0 to 4 kHz.

Figure 2. A snapshot from MBL software that reports the temperature and shows its effect on an animation of the associated molecular motion.

Figure 3. Graphs showing a) an MBL titration, b) a closeup of one equivalence point, c) the first derivitive of the data in b), and d) the corresponding second derivitive. The cross hatch is

a graphics cursor which has its coordinates displayed in the lower right.

Figure 4. An iconic representation of a simple model for unrestrained population growth.

Figure 5. A graph of the solution of the system specified in Figure 4. A constant birth rate of .1 per unit time and death rate of .05 per unit time was assumed.

Figure 6. Screen dumps showing a) a more complex model and a graph of its solution and b) the details "inside" the birth rate circle that relate birth rate to population.

Figure 7. A graph of MBL pendulum data (upper) and the solution of a dynamic model of the system. The data have been normalized for easier comparison to the model. The model assumes that friction is proportional to velocity.

Figure 8. A solution to a better model of the pendulum (curve) superimposed on data from Figure 7 (squares). This model assumes constant "oppositional" friction.