A HISTORY OF PROBEWARE

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“Probeware” —also called “microcomputer-based labs”, MBL, “Calculator Based Labs”, and CBL— represents one of the most valuable contributions of computers to education. By connecting probes to a computer running suitable software, students can observe real-time data in a variety of formats. When placed in an inquiry-based learning context, this capacity can significantly increase and speed learning.

The following is the first review of the development and dissemination of probeware. The goal in recounting this history is threefold. First, it is important to summarize what has been learned about probeware to guide educators and researchers interested in this area. I will try to summarize the literature, recount some unpublished observations, describe notable software, and speculate on lessons learned. Secondly, the story of the development and dissemination of probeware provides insights on educational change and the role of research and development. These insights are important for policy-makers and funders. Finally, the many people who have contributed to the development and dissemination of probeware need to be acknowledged.

THE BEGINNINGS

MY PERSPECTIVE

Although an academic history is usually written in the third person, this report is also a personal history, so I will depart from this tradition. So that the reader understands my decisions and mistakes, it is important to sketch out some of the background I bring to this history.

When I started my PhD program at Stanford in 1963, I intended to pursue an academic career in experimental physics. The civil rights movement, however, made such an esoteric path seem irrelevant, so I grabbed a MS degree after one year and took a teaching position at Stillman College, an historically black college in Alabama. My two years of teaching there both awakened a life-long interest in education and provided ideal training in education and insights on how to improve science education. The best curriculum materials then available seemed to fail to meet the students’ needs, so I resorted to my own observations and experiments. The clearest lesson I learned was that hands-on learning with good apparatus quickly generated intuitive understandings of complex phenomena. Once good intuitions were in place, the abstract, equation-based approach of physics was far more tractable.

Hoping for a combined education and physics PhD, I enrolled at MIT in 1965 on the strength of Jerrold Zacharias’s reputation in physics education (see Goldstein, 1992). In the end, I did a straight physics PhD with John King, a student of Jerrold’s, a master experimentalist, and dedicated educator. His ideas, intellectual generosity, enthusiasm, and willingness to take risks made a lasting impression. John was a national leader in physics education who advocated project-based learning and the importance of a set of sensors that could be used with an oscilloscope. His dream was a shoebox of sensors that students could use to measure almost everything (King, 1962). His approach to teaching was to give away every idea he ever had, and these seemed to come in an unending stream. His motto was “make mistakes rapidly”. In many respects, the probeware story is a direct continuation of his educational ideas.

CALC AND CALM

The Calculator and Laboratory Calculus (CALC) project at EDC directed by Bill Walton was the first educational application I ever saw that used real-time data acquisition. This was before 1970 when there were no microcomputers. Using a Wang calculator, a lab interface, and a x-y plotter, the researchers had developed some inspiring activities that helped learners improve their intuition about key calculus ideas. In one experiment, a photodetector counted bubbles produced by fermenting grape juice. The graph of the total number of bubbles over time is exponential as long as the yeast multiplies.

CALC probably never had much of a direct impact on education, especially as the idea of making alcoholic grape juice would be a non-starter in any school. It did help launch, however, the idea of intuitive calculus supported by numerical methods and interactive graphs. As the name reveals, the CALC project was very much on my mind when, in 1976, Hilton Abbott and I were funded by the National Science Foundation (NSF) for a project named Computer and Laboratory Mathematics (CALM).

The idea of the CALM project was to generate compelling computer-controlled environments that would teach logic and programming. Our favorite example was a model railroad that had switches and engine speed under computer control. We started the project with a relatively inexpensive Digital Equipment Company PDP-11 that implemented the 16-bit PDP-11 instruction set using three large Western Electric chips. That was too expensive for educational use, however, so we purchased a computer made from the brand new Intel 8008 eight-bit microcomputer. Before it was delivered, the manufacturer substituted the 8080 chip that turned out to be the foundation of the entire Intel line of microcomputers. We sensed the potential of these new chips and were continually updating our computers as better hardware became available.

THE KIM-1

During most of mid-1970's, I had assumed that the analog signals that are basic to most laboratory measurements were ill adapted to the digital world of computers. We had used digital outputs for the trains, digital inputs like the bubble counter or a train detector, and analog outputs like the train speed controller. But we had a blind spot for analog inputs such as temperature, light level, and voltage. Greg Edwards, a fellow physicist and program officer at the NSF whom I had befriended, set me straight. He was a futurist with a clear vision of future technologies who convinced me that analog-to-digital converters made computers the perfect laboratory instrument. At that time, he also introduced me to networking and made the fantastic suggestion that networking would revolutionize computers.

As a direct result of Greg's first suggestion, I added an analog-to-digital converter to the KIM-1 computer. A small company called MOS Technology had created the 6502 microcomputer that had an instruction set that was much like the PDP-11's in many ways. Because this was cleaner and more efficient than the 8008/8080 set, the 6502 was very attractive. To interest engineers in buying the 6502, MOS Technology built it into the single-board KIM-1 computer that it sold for $245 as an evaluation kit. The kit must have been successful, because the 6502 was sold to Motorola and became the microcomputer of choice for many companies, including Commodore, Atari, and Apple. This chip was the forerunner of the Motorola 68000 used in the original Macintosh, the Palm, and many other computers.

The KIM-1 had a tiny keypad, a six-digit hexadecimal display for output, 1K RAM, a 1K ROM monitor, and 16 digital input/output lines. The memory was amazing at the time, using eight Intel 2102 chips each of which was capable of storing 1,024 bits of memory! Programs were stored on an audiocassette recorder. We added a board that doubled the RAM, provided a socket for an EPROM (electronically programmable read-only memory), and supported analog input and output. With this board and a power supply, the KIM-1 became a complete, inexpensive laboratory computer.

To demonstrate the potential of this computer, we built a simple system for doing the cooling curve experiment. The KIM-1 could use the analog input to log the temperature of a sample of mothballs (phenyl naphthalene) in a test-tube. The temperature was measured by thermocouple and amplified by a simple 741 opamp circuit. The analog output generated a signal that could display the temperature history of the probe on an oscilloscope. Dick Lewis, our technician at TERC, mounted this experiment attractively on a display that we hauled around to numerous conferences.

THE COOLING CURVE EXPERIMENT

The cooling curve experiment became a powerful example of the educational potential of computers as lab instruments. Without a computer, students typically take an entire lab to gather the data for one cooling curve and then plot the data later. They often fail to understand the connection between features on the graph and the properties of the substance that is cooling. Having never seen a normal cooling curve, they often fail to understand that the plateau observed during a liquid-solid transition is unusual. Consequently, the key observation that the plateau represents the evolution of latent heat, is completely missed.

Because the probe is tiny and responds quickly, the sample can be small, too. This means that one cooling experiment can be completed in a few minutes. There is ample time to do a cooling curve without a phase change and then compare that to a curve with a phase change. Furthermore, students can see the temperature graph evolving as the experiment is underway. They see the solid start to appear as lovely snow-like particles at the beginning of the plateau and complete solidification at the end of the plateau. They can speculate about the reasons for the temperature being constant while the experiment is underway. If they are lucky, they can also observe supercooling. We even supplied a second sensor to measure the temperature of the surrounding water so students could verify that it was cooler and extracting heat, although the temperature of the mothball remained constant. We never formally evaluated the educational value of this approach, but it seemed obvious that we had found a greatly improved way of learning.

THE AAPT WORKSHOPS

By the late 1970's, the cooling curve example had generated considerable interest at meetings of the American Association of Physics Teachers (AAPT). A group of us led by John Layman developed a number of applications for physics teachers based on the KIM and our add-on board. To simplify the error-prone process of loading programs from tape, we burned a selection of applications into the EPROM.

The most ambitious and striking application involved capturing sound. Our analog-to-digital converter was fast enough to capture the signal generated by a microphone up to about 4 kHz. The software could instantly display the waveform on an oscilloscope, as well as its Fourier transform, which shows the frequencies present. One of my Amherst College students programmed the transform for his undergraduate thesis. He was able to squeeze the 256-term eight-bit transform into the tiny RAM by using the quick and efficient Fast Fourier Transform (FFT) algorithm. It was a triumph of coding to include a FFT in such a small amount of RAM.

We created a workshop for physics teachers from the applications in the EPROM and offered it at numerous national and regional meetings of the AAPT as well as Chautauqua short courses for college faculty sponsored by the AAAS. We shared the workshop development and delivery chores widely. John Layman at Maryland University and Pricilla Laws, at Dickinson College were responsible for many successful AAPT workshops. Al Woodhull from Hampshire College took over and improved the Chautauqua workshop.

BUT IS IT GOOD EDUCATION?

At this time, we first encountered three arguments against the use of probes that have continued to surface whenever we present the idea to new teachers. The first concern of skeptics is that by automating the lab, we lessen student interaction and learning. A truly automated experiment would, for instance, involve measuring the acceleration of gravity by having a robot pick up a ball, drop it, measure its time and distance of fall, compute gravity, and present the result. All the student would have to do is turn on the apparatus and read the result. I have actually seen experiments as automated as this, but certainly do not recommend this as a teaching strategy. The point of using probeware is not to automate the lab procedures. Good experiments that use probes still leave it to the student to decide what to measure and how to interpret the results. Frequently, the role of the probeware is to lessen the drudgery, increase the amount of experimentation students can undertake, and to show the relationship between the experiment and an abstract representation of the data.

The skeptic's second argument is that "suffering is good". We often hear statements like "I learned to graph the hard way by copying down long rows of numbers, so why should we make it easy for today's (lazy) kids?" This attitude helps explain why so few kids go into science. Certainly, if we can device ways of learning that are as effective while being faster and more inclusive, there is little reason to stick with the old.

The more thoughtful argument against probes is the "Black Box" objection. There is no way, the argument goes, that students can possibly understand everything that is happening in one of these experiments, so why should they believe the results or understand the underlying science? The combination of sensor, electronics, computer, and even the computer display, is a series of black boxes that students should not even try to understand. The point is, however, that for students to use probes effectively, all they need is to understand the relationship between input and output; they really can treat everything between as a black box. They can learn quickly, for instance, that an increase of temperature causes the line to go up on the display. In fact, the rise of the red alcohol in a thermometer is as much a black box. Science is full of black boxes and part of being a scientist is to focus on what is important and leave the rest to others. In fact, we are surrounded by black boxes within black boxes. To use the computer with which this manuscript is being written, is it necessary to understand how the flat display works? At what level is understanding necessary? Do I have to know how precisely how liquid crystals are influenced by voltage? Since liquid crystals are made of long molecules, do I have to understand their structure? The nature of covalent bonds and the origin of polarity? What about electrons and the Hamiltonian that determines their molecular orbitals and binding energy? There is an almost infinite regression of black boxes and it is absurd to maintain that understanding at all levels must precede use.

Concerns such as these made the AAPT leadership nervous about our workshop, so they asked Mary Budd Rowe and Lillian McDermott[1] to enroll in a workshop and evaluate what they saw. We were a bit intimidated by these well-known researchers, but the workshop passed their scrutiny with flying colors.

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[1] http://phys.washington.edu/cdb/personnel/@1113

After a few years, we had been responsible for purchases of hundreds of KIM computers and had introduced thousands of science faculty, predominately physicists, to the idea of real-time data acquisition in education. It turned out that we could not have planned a better dissemination strategy, because many of these physicist-educators had broad impacts in their own communities. Their early enthusiasm for probeware was undoubtedly responsible for its later acceptance.

THE ORIGIN OF "MBL"

By 1980, the idea of real-time data acquisition for educational purposes needed a name. I wanted the name to capture not only the technique, but also an open-ended educational approach that would distinguish it from automated labs or drill and practice with sensors. I was inspired by Seymour Papert's success at that time with Logo, in part because the name incorporated more than a programming language. "Logo" stood for constructivist education and the use of a general software tool to support an educational philosophy. Consciously following his example, I decided to name our approach Microcomputer Based Labs, or MBL for short. By doing this, I hoped to capture not only the idea of real-time data acquisition and display, but also a constructivist approach to using this tool for student exploration and discovery. Inventing the name also provided a way to track the impact of our work as we will see in the following sections.

The "microcomputer" in MBL dates the term. It was clearly appropriate in the era of KIMs and similar devices that were such small computers that they deserve the "micro" prefix to distinguish them from the array of more powerful computers then available. Today, desktop computers, although based on microcomputer chips, have shed the prefix. Consequently, the MBL name is outdated and we increasingly use "probeware", a term invented by Marcia Linn.

GRAPHICS AND NETWORKING

While teaching physics at Amherst College, I met Allen Siggia who, as a student at Amherst High had easily mastered most of the college physics and mathematics courses we had to offer. During the summer after his freshman year at MIT, he designed and built a complete PDP-11 work-alike computer from about 100 standard logic chips. He knew how to program the PDP-11, but had never seen its schematic, so his design was completely original and actually added some useful functions. I learned computer design just by studying Allen's elegant schematics. What I found most interesting, however, was the graphics display he had built into his project.

We were dissatisfied with using an oscilloscope as the graphics output from the KIM. In addition to being expensive, it was far less flexible than the graphics output from a computer. In this era before the Apple II, there were no inexpensive computers with graphics. We imagined implementing Logo and generating graphs from MBL experiments with inexpensive graphics. Therefore, I asked Allen for permission to use his design for a graphics interface for the then-popular computers based on the S-100 bus. The first hobbyist computer was the Altair, which used the 8080 chip and spread the computer out over several cards all joined by a bus consisting of 100 wires. This bus rapidly became a standard because many entrepreneurs offered CPU, memory, and interface cards one could mix and match to create ones own "S-100" computer running the CP/M operating system.

With Allen's help I adapted his graphics circuits to make a S-100 controller card and one to four memory cards that generated a 640 by 800 pixel display. Each memory card produced one bit for each of the pixels using 20 of the latest memory chips, the Intel 4116 dynamic RAMs each storing 16K bits. With four pixels we could generate 16 colors using a fast color look-up table or 16 gray levels. We displayed these on television sets we modified. One time, we made the wrong modification and managed to send high voltage from the TV to the computer and exploded chips on all five graphics interface boards!

The graphics interface allowed us to realize the dream of a low-cost computer for education that could do both MBL and turtle-based Logo. We designed software that could generate mixed text and graphics from BASIC which we called GRASIC, for Graphical BASIC. To keep costs down, we even developed a light pen that could provide input directly by interacting with the screen and obviate the need for a keyboard. Working with some gifted graduates from Hampshire College, we managed to realize Greg Edward's second prediction and create a networked version of CP/M we called the Networked Operating System, or NOS. The main purpose of this network was to share the expensive printers and hard drives of the time so that schools could provide multiple low cost computers in a lab setting.

Arthur Nelson helped us form Cambridge Development Labs (CDL) at this time to commercialize all our interesting hardware. CDL was spun off as a subsidiary of TERC to market the KIM boards, power supplies, graphics boards, as well as complete S-100 computers that incorporated the graphics, NOS, and specialized software. While organized as a for-profit, we were clueless about business and lost lots of money. Arthur had enormous patience with us and eventually recovered some of his losses by converting CDL to an educational software catalog operation.

TERC WORKSHOPS FOR TEACHERS

Through the late 1970s, our MBL work had been funded through a succession of NSF grants to Springfield Technical Community College and TERC, then known as the Technical Education Research Centers. Ronald Reagan took office in January 1981 having run against a federal role in education. He soon managed to eliminate the Education Directorate of the NSF and one of the Department of Education's Regional Labs. By that fall, our grants ran out and TERC had no federal funding for the first time since its founding in 1965. To keep TERC alive, we went on the road, giving workshops on computers in education throughout the country.

We hauled about 40 microcomputers around the US and Canada for these workshops: a mix of Apples, our own S-100 graphics computers, seven Compucolors, Ataris, Sinclairs, and a dozen TI-99's that had the first commercial implementation of Logo. Several of us would arrive at Logan airport with a huge pile of boxes containing the computers and materials. In those less stressed days, we could slip the Skycap $5 for each extra box and not have to pay excess baggage fees.

Tim Barclay, Dan and Molly Watt, and I were the mainstays of these workshops, but we were assisted by many other early pioneers. We offered 12 different one-day workshops over three days in four parallel sessions. The workshops included language instruction in Logo, BASIC, Pilot (a lesson authoring language from Apple), and Pascal, overviews of applications in math and science, and some popular probeware workshops. We sometimes offered the AAPT MBL workshop using KIM-1 comptuers, but by now we were also using the Apple II and that provided a simpler, less intimidating way of doing probeware.

THE APPLE GAME PADDLE PORT

The Apple II had a game paddle port that we were able to use for probes. The game paddle was simply a variable resistor, measured by using the CPU to count how long it takes for a capacitor to discharge through the variable resistor in the game paddle, up to a maximum of 255. By substituting a sensor that generated a variable resistance, we were able to get data into the computer. It also turned out to be simple to modify the software to count higher, we could get a more accurate measurement over a larger range of resistances.

The simplest sensor to substitute for a game paddle is a photodarlington light detector. In our workshops, we had participants connect a one-dollar FPT-10 light sensor to a header that fit into the game paddle port and then write a three-line BASIC program that graphed the resulting data. The system was fast enough to pick up the 120 Hz variation in florescent lights, a measurement that never failed to impress because the sensor could detect something all around us that our eyes miss. Although simple in the extreme, the experience was so empowering that many participants felt that they could go on from this experience to create far more complex probe experiments.

Workshop participants did not necessarily make all their own electronics. We designed a "Blue Box" that connected to the Apple game port and made the four built-in analog inputs, two digital inputs, and two digital outputs available for experimentation. A collection of temperature, light, and voltage probes could be connected to the Blue Box through standard RCA connectors. We wrote a variety of short BASIC programs that utilized this interface and even provided suggested student activities. These were very popular, because what teachers learned in the workshop, they could use the next day in their teaching.

It is amazing what we were able to do with the primitive game paddle inputs. One of my favorite demonstrations from that time was to actually use a game paddle as a sensor. By taping a long metal rod to one game paddle that is held so that the axis of rotation is horizontal, one can make a functional pendulum for which the pivot is the game paddle knob acting as a rotation detector. A simpler apparatus can hardly be imagined, but it has considerable depth as an apparatus for investigations.

Graphing the game paddle resistance as a function of time gives a periodic function, which is a nice example of a sine wave in nature. After a bit of experimentation, one can see that the period is constant for different amplitudes. On closer observation, it is possible to observe longer periods for large amplitudes and a flattening out of the sine wave for very large amplitudes. There is still more to see in the decay of the amplitude over time. The standard textbook treatment of damped harmonic oscillators predicts that the envelope of the sine waves is a decaying exponential, but a close look at the data shows that the envelope is a straight line. This observation can be explained by looking closely at the apparatus and finding that there is considerable friction in the pivot. A simple model of a pendulum with friction can be adjusted to fit the data perfectly.

This pendulum experiment is a nice example of the way investigations with probes can go to different depths, depending on learners' level of sophistication. For some students, discovering the lack of dependence of period on amplitude would be exciting and as much as they could absorb. More advanced learners might go on to looking at large amplitudes, damping, or even modeling. All this and more is enabled by getting real-time data into the computer, even through the limited game paddle port.

OUTGROWTHS FROM THE WORKSHOPS

From a financial point of view, the TERC workshops were a huge failure. If we sold 80% of the available seats, we broke even, but at some locations we failed to make this goal. Without the financial and moral support of the TERC Chairman, Arthur Nelson, the organization would have never survived. From a dissemination perspective, however, we were doing just the right thing. We inevitably reached the future leaders of school technology implementation, so there were people everywhere ready for the next step.

We were in no position to measure the impact of these workshops except through antidotes that we happened to hear. One that always inspires me is the story of David Vernier, a physics teacher in a workshop we offered at the Oregon Graduate Center in Beaverton, Oregon. He was so impressed by the educational potential of MBL that he went on to start Vernier Software, a company that is today a leading probeware provider. One of the current leaders in educational technologies for special students, Chuck Hitchcock of CAST, first saw the potential of technology at one of these workshops.

Another spin-off from the workshops was the publication of the first commercial probeware packages. Adeline Naiman, who worked for TERC on development, urged me to collect some of the more interesting experiments from the workshops into a set of experiments with lab instructions and teacher notes. She talked HRM Software into publishing “Experiments in Physiology” that included experiments for measuring physiological measures such as heart rate, breathing rate, skin conductivity, flicker fusion, and response time. The kit included everything a teacher needed to get started: a Blue Box, wires, ten short programs (Apple only), probes, and a manual. This kit was very successful and was quickly followed by “Experiments in Science” that also drew on the workshop.

HRM CHEMISTRY SOFTWARE

Acting on a hunch that chemistry teachers would be quite interested in pH measurements, we developed another package in HRM’s “Experiments in…” series: Experiments in Chemistry. Since we had no funding, all the development was done either at night and weekends or by Sister Diana Malone, a chemist who took her sabbatical from Clarke College in Dubuque, Iowa with us.

The Experiments in Chemistry package featured a glass pH electrode connected to the Blue Box through a second amplifier box; a bit of a kluge, but inexpensive. The most impressive experiment was titration. When acid or base was steadily added to a solution, a graph of its pH against time goes through one or more sudden drops, depending on the valence of the anion. The phosphate ion, which can bind with three hydrogen ions, exhibits an impressive three steps. We were also able to design experiments on reaction kinetics, chemiluminescence, exo- and endothermic experiments, and latent heats.

The software for Experiments in Chemistry was the first integrated MBL package. Previous packages had used small, separate programs for each experiment. This limits the flexibility of the software and the range of explorations students can undertake. My goal was to make one package that could handle all the experiments and contained a rich range of general analytical tools. The software contained several calibration functions, a flexible grapher with autoranging, log and linear scales, least-squares fits, and a variety of analytical functions. Using the BASIC enhancements from the MBL project, I was able to make squeeze this all into the two 64K blocks of RAM the Apple II could support.

The unusual flexibility of the software and the sophistication of the experiments helped ensure its warm reception. Experiments in Chemistry was a commercial success and won a prize for best software of the year. Perhaps because we kept the development costs low, the sale price was acceptable to a substantial number of schools and colleges.

OUR FIRST CLASSROOM STUDIES

Anticipating some funding in the near future, Tim Barclay and I arranged in 1982 the first classroom studies of probeware with children. Our first challenge was the hardware. Given the range of small computers then available, we decided to move away from the Apple-specific game port and use the RS-232 serial interface that every computer had. We reasoned that using a standard like RS-232 for our lab interfaces, although less-than-ideal for analog measurements, was better than any computer-specific approach. Stephen Bannasch and I designed an analog converter that generated a serial stream of raw data from whatever sensor was attached.

We decided to use our Compucolor computers because they were easy to carry and set up. Also, they were reliable and we had seven of them, more than the expensive Apples. They combined computer, monitor, and disk drive in one unit. Just add the keyboard and our serial interface, and we had a complete computer capable of lab measurements. While it lacked true graphic capability, the Compucolor had an extended character set that included little dots suitable for graphing points. So, with a bit of hacking, I was able to read the data stream and make a colorful display with graph, digital readout, and controls.

Tim selected a fourth grade in a mid-income area of Arlington with an agreeable teacher who was also a friend. It was fortunate that we were ignorant of what was taught at fourth grade. I had not realized that students were not supposed to know about graphs and decimals. The display showed temperature to a tenth of a degree while also graphing the time history of one or two temperature probes.

On our first day in the classroom, we carried in two computers and tape recorders. As the kids clustered around, we booted up the software and challenged the students to figure out what part of the sensor was sensitive to temperature. In the few minutes that it took to find some hot and cold water, unpack and start the tape recorders, the kids had figured it all out. We failed to record their thinking, because it all happened so fast. Not only did the kids immediately figure out that the tip of the sensor was sensitive to temperature, they also figured out decimals and the graph.

Although we missed recording it, I distinctly remember kids wondering about the extra decimal. My display would show 35.0 as 35, so there was some confusion about the relative size of 34.9 and 35. If you ignore the decimal point--a natural thing to do if you don't understand it--34.9 looks like 349, which is much larger than 35! By warming and cooling the probe, the kids immediately figured out that 34.9 was near 35 but cooler.

This was our first indication of the power of kinesthetic real-time interactions to lead to understandings of abstract representations. In effect, kids were using their sense of temperature and the exquisite sensitivity of their fingers to map their experiences onto the computer display. They could feel the temperature change and, at the same time, see the numbers change. A slight change in temperature causes a change like 34.9 to 35, so these two numbers must be near. In effect, the computer can count in decimals for them as they control the temperature, going through sequences like 34, 34.1, 34.2, … 34.9, 35 as they warm the probe. Students, who had often been asked to count, liked making the computer count. Their short exposure to the apparatus appeared to make decimals seem obvious to these children.

Similarly, graph interpretation yielded to kinesthetic real-time interactions. The kids could see the graph marching regularly from left to right while rising and falling according to the probe temperature. They immediately thought of it as a kind of Etch-a-Sketch and tried to make a city skyline. Because vertical lines are impossible, they failed at this task but quickly learned something about the graphical representation. In fact, we later observed a case in which they put too much reliance on the details of the graph.

Our primitive interface box would sometimes generate a lot of spurious noise. On one later visit, the result was a graph that had jagged peaks and valleys added to the graph. The children were puzzled by these features and tried to explain their origin. Their observations all concerned why the probe might be warming and cooling quickly. They wondered whether the water had different temperatures or whether light falling on the sensor changed the temperature. It never occurred to them that the electronics was faulty. So, while their reasoning was incomplete and wrong, it was completely logical and indicative of a solid understanding of the graph and what it was supposed to tell about the temperature at the sensor.

We also noted some weaknesses in student mastery of the graphs. Their understanding was qualitative, but not quantitative. They could identify the section of a graph representing the hottest or coldest temperatures and even where the temperature was changing most quickly. This was exciting because it meant that they could interpret graphs and had some intuitive calculus ideas. They could not, however, tell you what the temperatures were on the graph or the time intervals between graph features.

These informal observations, which we never published, convinced us that the real-time interactions using probeware had a powerful ability to teach both science concepts and data representations like graphs and decimals. They gave us the courage to apply for funding from several sources.

THE VOYAGE OF THE MIMI PROJECT

By 1983, Reagan had lost his zeal to eliminate education. A series of reports culminating in "A Nation at Risk"[2] released April 1983, raised national concern that education was in trouble. Consequently, research and development funding resumed, although the NSF never re-established an Education Directorate. After a hiatus of two years, we were able to resume grant-supported work on probeware.

THE GENESIS OF THE MIMI PROJECT

Our first grant-funded work after the Reagan hiatus involved producing the probeware component of Bank Street College's Voyage of the Mimi project. The project was conceived by a group of people assembled by Dick Ruopp, then president of Bank Street College of Education. Adeline Naiman and I from TERC participated in exciting meetings of this group along with others from Bank Street.

"Mimi" was proposed to Frank Withrow at the Department of Education as the first major multimedia educational project. It addressed math and science concepts at grades four to six. An excellent package that is still marketed by Sunburst, it is based on the idea of showing kids that they can be scientists. In the first "season" of the Voyage of the Mimi which this funding produced, students view broadcast quality videos that show youngsters helping graduate students doing research on a sailboat named "Mimi" captained by its real-life owner Peter Marston, then a physicist at MIT. The youngsters in the video are studying whales and along the way they measure water temperature, light transmission, and whale sounds. In the videos they actually use one of our Apple computers that we modified for battery operation.

In order to bring home the idea that kids could be scientists, similar experiments with temperature, light, and sound are done in school using a probeware hardware and software package we developed. We designed a special board for the Apple for these experiments. It had a faster and more accurate analog-to-digital converter than used in the game paddle. It also had a digital multiplier that sped up some of the calculations required for the sound experiments. Much later, Sunburst built a replacement interface for the Macintosh which by then was sufficiently fast to not require a hardware multiplier.

The hardware also incorporated a unique "self-identification" scheme for the probes. There were two input ports and any of four sensors could be plugged into the ports. As soon as the user changed what was plugged in, the hardware would sense the change and be able to identify what probes were present. The software was aware of this and would present the user with appropriate choices. This eliminated meaningless options and greatly simplified user experience. As soon as the appropriate sensors were plugged in, the software was ready to go, making it the first "plug-and-play" general-purpose probeware software.

MIMI SOFTWARE

I implemented some valuable user interface ideas for the Mimi project that have never been duplicated. In addition, we were teamed up with Jan Hawkins, a gifted researcher who studied student learning in real classrooms that used our software. Her feedback substantially altered the software design and helped contribute to the success of the project.

The Mimi project was intended to be as inclusive as feasible. It featured a multi-ethnic team of kids and a deaf researcher and it was intended to be effective with students with mild learning disabilities. Consequently, we wanted our software to be understandable by the widest range of kids and to include a variety of representations that could be adapted to the needs of special students.

Because of the problems we observed in Arlington with student understanding of the graph scales, I added several activities designed to focus student attention on the scales one at a time in simplified contexts. The first time students saw temperature on the screen, it was represented as a thermometer with a red "mercury" column that moved up and down next to a temperature scale. Students could change the range of on the scale and we designed a series of exercises that focused on reading the temperature from the scale. They could also switch between Fahrenheit and Celsius or see both at the same time. The scale looked exactly like the vertical scale they would later see on graphs, and changed scale the same ways. I also could show moving columns representing light in lux and sound volume in decibels.

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[2] http://www.ed.gov/pubs/NatAtRisk/

Next, I introduced the horizontal time scale alone in a format that could be used as a timer. A vertical hash mark moved left to right along a time scale and left an image of itself whenever a key was pressed or there was some change in sensor. After the moving hash mark exited to the right, the user would see one or more vertical lines “left behind” that represented when some events happened.

This general-purpose timer could be used to measure response time, the time between light flashes, or the time needed to warm a pot of water. To use the timer, the user had to set the axis to a reasonable range and read the time from the time scale. The scale was identical with the horizontal scale later used on the graph, and the manipulations needed to set the scale appropriately were exactly those used in the graph. Since reaction times are fractions of a second and other experiments could take thousands of seconds, this provided valuable experience with setting, reading, and interpreting the time scale.

My next idea was to introduce the graph by having students move the thermometer from left to right. We thought that a graph was confusing because it involved coordinating two separate quantities, time and temperature, or whatever was being measured. The way a graph moves automatically from left to right with time might be perplexing at first, so we reasoned that having students provide the movement would help clarify the relationships.

My design started with one “live” thermometer on the left of a blank screen. Its “mercury” column would move up and down in response to the temperature sensor. When the user hit a button to “freeze” the thermometer, the column would stop moving, representing its last value before freezing. At the same time, another thermometer would appear to its right that was “live”. After five freezes, the screen would show five thermometers displaying the temperatures at successive times the student pressed the button.

While these ideas might have been solid, this implementation was even more confusing and was dropped as a result of Jan’s careful classroom observations. The word “freeze” was unfortunate and confusing, and the way new thermometers popped up on the screen was distracting. The “freeze” button seemed to create a new thermometer; that it also saved the last value on the previous thermometer was easily overlooked.

Our next step in the transition to a regular graph worked so well that the five-thermometer approach was unnecessary. We implemented a moving thermometer. As the thermometer moved steadily from left to right, its “mercury” also moved up and down in response to the temperature at the probe. The thermometer’s scale, however, stayed behind at the left side of the screen. The now-familiar horizontal time axis was also drawn. The moving thermometer could also leave behind a trail of dots emanating from the top of the “mercury” column. When the thermometer reached the right side of the screen, it vanished, leaving a standard temperature-time graph. Of course, the thermometer could be toggled off; the result was a standard graphing tool.

Jan’s classroom observations indicated that the moving thermometer was a success. By following the sequence of activities focused on the two scales separately, students could make both qualitative and quantitative interpretations of data displayed in the graphs. This seemed to work equally well for temperature, light, and sound volume.

THE SONOGRAM

We never studied one of the most interesting parts of the Mimi probeware software. Because the frequencies of whale sounds are so important, we implemented the FFT algorithm that we had developed for on the KIM, but with a sonogram-like output that indicated the intensity of the sound at each frequency over time. A student could see, in real-time, a representation of speech or other sounds picked up by the microphone. Sonograms from two sounds could be displayed on graphs one above the other for easy comparison. The transparency of this representation and its power as a tool for exploration was brought home to me by an incident with a non-English speaking child.

Frank Withrow invited me to demonstrate our Mimi software in 1984 at an international conference in Geneva, Switzerland. One afternoon a Russian child visited my exhibit. Communicating entirely by gestures, I showed him how to use the microphone to generate sonogram displays. He intently compared displays of his voice sounds to sounds made by banging and hitting things. After ten minutes of puzzled absorption, some light went on in his head that he struggled to put to words. Finally, he said “same thing!” and strode off all smiles. Much later, I surmised that he had not realized that voice had the same physical basis as other sounds. This is reasonable, since we speak without conscious effort in order to communicate from mind to mind. That fact that this communication between sentient beings shares physical properties with sounds from inert objects could be surprising. If this was what this child was thinking, it is an unusual misconception, but one that was important for him to correct at that time. It is wonderful that, without being pre-programmed to weed out that misconception, the probeware tool could be used to eliminate it through exploration. This incident has always underscored the importance of exploration as a learning strategy.

In an effort to disseminate the probeware portion of the Mimi project separately from the huge and expensive Mimi package, we developed a “Bank Street Lab”. It featured Mimi’s hardware and software, with new experiments suitable for middle schools. Unfortunately, the publisher of Mimi, who was interested in this extension, was bought by another company, which was bought by a third. In the resulting confusion the entire Mimi project was lost for awhile but was eventually spun off to Sunburst, that was recently sold to Houghton-Mifflin. The lab, on the other hand, resurfaced as “Whales and their Environment”. This was not the last time that chaos in the publishing world inhibited getting probeware to market.

THE MBL GRANT

In 1983 we received three years of funding for probeware development from Andy Molnar’s Applications of Advanced Technology program at the NSF. The grant name “Microcomputer Based Labs”, helped establish the name and the educational ideas it encompassed. John King and I were co-Principal Investigators on the project.

It was an energizing opportunity finally to have the resources to understand more about student learning with probeware as well as to develop some more sophisticated software and curriculum materials. The generous funding allowed us to go in several directions at once: research, technology development, curriculum development, and dissemination. We organized research under Jan Mokros with input from John Clemmet and hardware development under Stephen Bannasch. Ron Thornton from Tufts joined us half-time to work with Tim Barclay on the experimental activities.

THE ULTRASONIC MOTION DETECTOR

The most important development of the MBL grant was entirely serendipitous. During a sabbatical year with us on leave from his physics faculty post at Whitman College, Jim Pengra took the first steps in developing the ultrasonic motion detector. Much later, Andy Molnar frequently claimed that he would have been delighted with the impact of this award even if nothing else ever came out of the MBL grant.

The previous year Polaroid Corporation had introduced the Sun camera, the first commercial camera to incorporate automatic focussing. It used a remarkable transceiver that emitted an ultrasonic pulse and then listened for the echo of the pulse. When the user pressed the button on the camera, the transceiver emitted a pulse and a motor started changing the focus on the camera’s lens from near to far. When the echo was detected, the electronics triggered the shutter to take a picture. The mechanism was adjusted so that the lens would be in focus for whatever generated the echo. In collaboration with Texas Instruments, Polaroid had developed an inexpensive pair of integrated circuit chips to handle most of the signal processing. In an effort to exploit its investment in this technology, Polaroid created an experimenter’s kit that suggested other applications. Both Stephen Bannasch and I had bought kits but had not found time to explore their educational applications.

Having Jim join the team with no specific duties was just what we needed. Although we had generous funding, it took the extra flexibility of a volunteer to make the most significant development. I asked Jim to link the Polaroid transceiver to an Apple and see whether he could make it work continuously. If that was possible, we could measure the distance to an object as it moved. Knowing position as a function of time, we reasoned that we could compute velocity and acceleration as well. Since no inexpensive sensors were available for position but its measurement was essential to understand the physics of motion, we were very interested in the Polaroid device.

In one week, Jim had the ultrasonic detector working with an Apple computer through the digital lines in the game port. He wrote a simple program to graph position, velocity, or acceleration. He found that there was no problem in running the transceiver at high speed. The only limitation was that the software had to wait for one pulse to return as an echo before sending out the next. Sound travels in air about one foot per millisecond, so the maximum range of ten meters requires 60 ms round trip, limiting us to around 10 measurements per second.

The ultrasonic motion detector generated an enormous amount of excitement, particularly in the physics community. We developed a number of popular demonstrations of its capacity. One of the most impressive measured the velocity of a can rolling up and then down an inclined plane. To engage the audience, I would ask everyone to sketch their prediction of the velocity of the can as a function of time. With the detector at the top of the ramp, the most common predictions were a) and b) in Figure 1

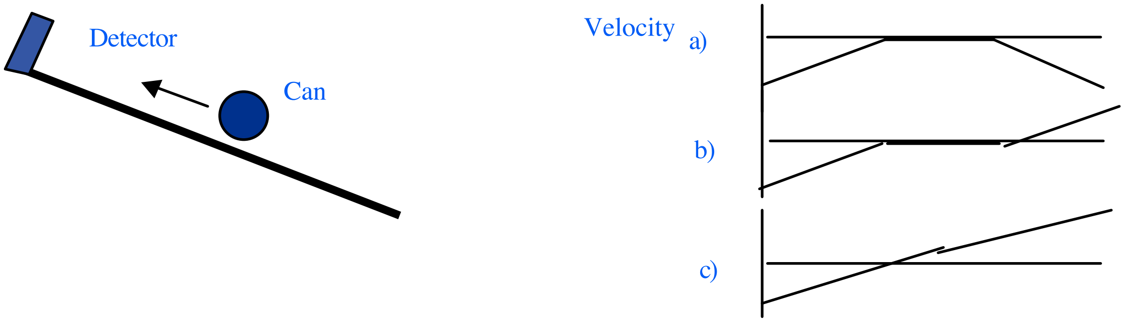

***Figure 1. A schematic of the rolling can experiment** and typical predictions of the time history of the velocity of the can after being launched upward as shown at the left. The audience is usually told that the can starts with negative velocity since it is moving toward the detector. Most believe that the can stops for a finite time before rolling down, and so select a) or b).*

The correct answer is revealed by doing the experiment; the graph goes smoothly through zero velocity as shown in c). Contrary to most peoples' perception, the can stops only for a vanishingly short instant. On closer inspection, the graph has a slight kink at zero velocity, with a slightly smaller slope afterward. This is because the slope of the velocity is acceleration and the acceleration is mostly due to the constant gravity, but also includes a contribution from friction and that changes direction when the can changes direction.

The ease with which experiments like this could be done with the motion detector generated tremendous interest. To respond to this interest, we made a kit consisting of some notes, Jim's software, and the adapter he made to connect the Polaroid kit to the Apple. We disseminated hundreds of these kits with the goal of inspiring others to develop the ideas further. At least one company sold an assembled version of the kit using Jim's software without modification.

FORCE DETECTION

We needed a force detector that could work with the motion detector. If we could measure the force on an object at the same time as its acceleration, students could experience Newton's second law. This central concept is traditionally difficult to teach because of the many misconceptions that students bring to this topic. Perhaps a good sequence of real-time experiences could substantially improve student learning of Newtonian dynamics.

We struggled to produce an inexpensive force detector. The standard technique, using a strain gauge, seemed unnecessarily expensive. In the end, we came up with a novel solution based on an inexpensive Hall effect sensor that measures magnetic field. We placed a permanent magnet on a brass band that could be deflected slightly by an external push or pull. The movement would change the magnetic field sensed by the Hall effect sensor. Although the relation between magnetic field and distance is non-linear, its change as a result of small displacements is linear, to a sufficiently good approximation. We built into the force probe a digital-to-analog (DAC) converter that generated a DC offset to equal the signal generated by the Hall sensor when no force was applied. The difference between this DAC output and the Hall sensor's output was a linear function of applied force. I always liked this probe because it was inexpensive and served as a magnetic field detector in addition, for no added cost!

HEAT AND TEMPERATURE

We hoped to have the same kind of breakthrough in learning about heat and temperature as we had achieved with kinematics and dynamics. The central problem that students trip over when learning about thermal physics is distinguishing heat and temperature. Heat is a form of energy; adding heat to an object usually, but not always, increases its temperature. This close association between added heat energy and temperature change is at the root of many student misconceptions. We reasoned that we needed a way of focusing on the differences between heat and temperature.

Part of the problem is that there is no way to measure directly the heat energy in an object. We explored the feasibility of measuring the heat added by designing a heat flow sensor. A possible candidate was a device called a thermoelectric cooler that is used to cool kegs of beer electrically. This is a sandwich of metal junctions that converts electrical current to a difference of temperature. This effect is reversible, so that a temperature difference across the sandwich generates a voltage. Because a temperature difference can only be maintained if heat flows through the sandwich from hot to cold, the voltage out is a measure of the heat flow. The sensor works, but is expensive and hard to use. In the end we abandoned it because we had a better idea.

Instead of trying to measure heat flow, we developed a "pulser" that would deliver a fixed amount of heat, which we named a "dollop". We realized that not all our interaction with an experiment had to have data flowing into the computer. The pulser was an example of a controller that was in a sense the reverse of a sensor. A controller generates an output that influences an experiment. Our pulser was an immersion coil used for heating liquids. Every time the student requested a dollop, the coil was turned on for a fixed time. Because the inexpensive coils that run on 120 VAC are hazardous, we used a 12-volt version designed for use in automobiles. This substantially increased their cost but made them feasible for classroom use.

Students using a pulser would gain experience with the effect on temperature of adding a fixed amount of heat. A succession of such experiences should help clarify the differences between heat and temperature. It proved very effective, for instance, for students to experiment with the effect of one dollop of heat on the temperature rise of different amounts of water or the same amounts of different liquids. When dollops are added to an ice-liquid mixture, the temperature doesn't change at all, but some of the ice melts. Clearly, the heat goes into melting the ice and cannot raise the temperature until all the ice is gone. Experiments like these should be helpful in teasing apart heat and temperature. Marcia Linn (see below) used this apparatus over a decade to gather detailed information about student learning of thermal concepts.

MBL INTERFACE AND SOFTWARE

Although the motion detector, force probe, and pulser were our most significant technological breakthroughs in the MBL grant, we made a number of other important advances, as well. We developed a new interface for the project, called the "Red Box" that plugged into the Apple II game port. This made the project Apple-specific, but this was not a problem at the time, since Apple then dominated the educational market. Unlike the Blue Box, the Red Box contained significant electronics that improved its performance and convenience, It was sufficiently simple, however, to be far less expensive than the Bank Street board.

The problem in electronics design for education is not in producing sophisticated circuits, but in finding the right balance of price and performance. Educational hardware has to be sold for approximately seven times the cost of the component parts and the labor to assemble them. This "times seven" rule seems like unconscionable gouging when you first hear it. I am, however, convinced that it is reasonable, given the costs of development, the small size of the market, the high costs of sales and support, and the huge educational burden companies must assume to sell technical products. Companies that try to sell product for less seem to fail.

Because of the times seven rule, we were very careful about the parts used in the Red Box. We used inexpensive parts because every extra dollar in parts costs added seven dollars to the list price. The Red Box had four identical ports that each used the standard six-conductor telephone connector. Any probe, whether digital or analog, input or output, could be connected to any port. Like the Voyage of the Mimi hardware, the probes were self-identifying, so plug-and-play software could be designed.

We also developed a broad array of machine-language software enhancements that extended the BASIC that came with the Apple. This added many features including the construction of user menus, support of Red Box functions, swapping code in and out of memory during execution, named subroutines, local variables, and line-number free programming. These, in turn, made it feasible for non-professional programmers like me to write increasingly sophisticated MBL software.

MBL RESEARCH: KINEMATICS

One aspect of our MBL project was undertaking educational research and simulating others to do likewise. The ultrasonic motion detector provided particularly rich grounds for research. We collaborated with John Clemmet to look at student misconceptions. We found that a common misconception was that with students no exposure to probeware looked at graphs as stages on which events were enacted.

We were amazed at the ease with which students were able to interpret graphs of motion using the ultrasonic motion detector. As Tim and I had discovered earlier, even when students had not been formally introduced to graphs, they were consistently able to interpret features of position versus time graphs. Jan Mokros and I (1987) found that, if students walked back and forth in front of the motion detector while observing a graph of their motion, they would then quickly learn to interpret position graphs. The usual assumption is that students need to be able to produce graphs before understanding them. Graph production usually consists of converting a set of pairs of numbers into a graph. Our finding was that graph production was independent of graph interpretation. Students could interpret graphs without being able to produce them. Conversely, another study of college freshmen engineering students found that these students could produce graphs but were unable to make the kinds of interpretations that we found elementary-grade students could do after only a few minutes with appropriate probeware.

We held research sessions at two MBL conferences with the goal of stimulating collaborative research. One outcome of this was some interesting research undertaken by Heather Brassell (1987), a student of Mary Budd Rowe's. Mary had shown conclusively that "wait time", at least a ten-second delay between a question asked by a teacher and supplying an answer, would dramatically increase student participation and learning. Because of Mary's long-standing interest in wait times, she figured that some delay between an experiment and the display of a graph derived from that experiment would be helpful. To test this, Heather taught the same kinematics lesson three ways: one using real-time graphs with a motion detector, one using a motion detector but a graph that was displayed only when a ten-second experiment was complete, and one covering similar topics using overhead slides. The results were unequivocal: only the simultaneous display of the real-time data resulted in significant learning.

Ron Thorton, while on staff at TERC made important contributions to the MBL project. He developed a sure-fire way of using the motion detector to teach the basic ideas of kinematics, the description of motion. The recipe consisted of six steps:

1. Have a student walk back and forth in front of the motion detector while observing the resulting position-time graph. Sketch a graph directly on the display and then try to match that graph by walking back and forth.
2. Explore the position graphs of the motion of some inanimate objects.

3-4. Repeat the previous two steps for velocity-time graphs.

5-6. Repeat the two steps for acceleration-time graphs.

The coupling of the kinesthetic experience of the motion with the motion of an inanimate object seemed to be particularly powerful. As in our prior studies of temperature, light, and sound, learning seems to be greatly enhanced when a body experience was coupled with an abstract representation of that experience: the graph representing the history of that experience. We suspect that the very fast feedback between experience and representation helps clarify any misconceptions or errors. When a student intends to move the graph in one direction and sees that a particular motion has the wrong effect, he or she can instantly make a correction. The speed of the feedback means that many such corrections can be made very quickly.

Back at Tufts, Ron Thorton and his colleagues continued to study this sequence in many contexts over the next decade. They consistently saw that students learn qualitative kinematics and dynamics concepts better through this sequence that through any other combination of traditional labs, lectures, homework, and demonstrations. With the addition of a force detector, these results were extended to dynamics. Similar results were found for other physical parameters such as voltage and current.

HOW NOT TO DO MBL RESEARCH

Another initiative funded in the latter part of the Reagan presidency was the Educational Technology Center (ETC) at Harvard directed by Judah Schwartz and David Perkins. This was by far the largest research effort at that time designed to look at how technology could improve mathematics and science learning. ETC decided to concentrate on math and science concepts that were considered difficult to teach and to explore ways technology could improve student understanding of these concepts. A sub-project using probeware was launched to address persistent student difficulties with understanding heat and temperature. A study group consisting of teachers, researchers, and scientists was formed to design and conduct a study.

While most of the ETC research was thoughtful and made important contributions to our understanding of educational technology, the probeware sub-group was a failure. In a misguided effort to honor their experience and knowledge, the design of the educational experiment and materials was left entirely to the teachers in the study group. A strictly controlled experimental design was selected in which the same teacher taught the same cooling curve labs with and without computers. Since the computer class could have an "unfair" advantage because it is easier and quicker, it was hobbled so that exactly the same experiments were done in both labs. The extra time in the computer lab was spent giving students detailed step-by-step instructions on how to use the equipment, which they had never seen before. The natural advantage of speed and flexibility in the probeware lab was eliminated by design.

Not surprisingly, no significant difference in student understanding of heat and temperature was found between the two groups. Many researchers interpreted these results as proving the failure of MBL, but it simply demonstrated that technology *per se* offers no advantage; it must be exploited through appropriate instructional strategies.

MBL CURRICULUM AND DISSEMINATION

A major goal of the MBL project was to disseminate the MBL idea as broadly as feasible. We employed a number of strategies to accomplish this: developing curriculum materials, holding two conferences at Tufts, distributing low-cost kits, talks at conferences, and distributing the materials through commercial channels. The conferences were important because they stimulated research and generated excitement for the MBL idea. The TERC newsletter, *Hands On!*, and countless presentations at conferences also helped build interest. Our primary dissemination strategy, however, was to develop, test, and market a series of instructional units that used probeware. The NSF expected us to disseminate our materials by finding a commercial publisher. We were able to solicit bids from four publishers and then selected HRM Software based on criteria that we hoped would ensure commercial success.

We were always ambivalent about the degree of detailed directions in our curriculum materials. The power of good probeware is that students can use it to explore anything. As scientists, our interest was always in making more powerful, general tools that would maximize the range of experiments that students could undertake. Our dream, one I inherited from John King, was to provide a shoebox of sensors and controllers that could be used to instrument almost any experiment a student could dream up. (King, 1962)

Our drive toward open-ended tools proved impractical in most classrooms. The middle school teachers who tested our materials wanted focused activities with clear learning objectives, detailed instructions, and easy student evaluation. Our classroom observations made us quite sympathetic with this view. Students unfamiliar with the software needed instructions; open-ended questions were baffling and students who are confused usually waste time. We undertook time-on-task studies to determine how productive students were. We found that when we provided clear, detailed instructions, student time on task increased and was higher than in conventional labs.

These in-class experiences led us to design very detailed laboratory activities for our published curriculum, particularly the first experiments. We reduced the structure in the later labs and included some open-ended challenges, but we always felt that we had lost something along the way. If the only published examples of probeware were highly structured, we worried that the ultimate power of the approach would be lost. Our consolation was that teachers who did not need the structure would simply ignore the curriculum and invent their own, whereas the teachers who did needed structure would find it in the materials.

To foster close contact, HRM hired Adeline Naiman for product development and based her in the TERC building. The MBL project eventually completed and tested four units aimed at middle grades, starting with one based on the motion detector. Unfortunately, HRM went bankrupt after a few years. I have always felt badly because our designs may have contributed to this. There is an entire field of manufacturing engineering that takes prototypes of products and re-designs them for ease of manufacturing and high reliability. HRM simply duplicated the designs we had developed for field testing. These were not designed for manufacturing and they were not sufficiently reliable for use in the rugged environment of teaching labs. We urged HRM to subject our designs to manufacturing engineering, but they lacked the resources to invest in this step. When HRM dropped its entire software line, the MBL units continued to be sold by Queue, Inc. but were lost in their catalog of hundreds of titles of varying quality.

TRACING MBL EXPANSION

The lack of commercial success of our MBL project, however, did not significantly slow the dissemination of the **idea** of probeware. One of the best things to come out of the project was, perhaps, the MBL label, because we could use it to track our wider impact. Presumably, everyone using “MBL” or its derivatives like “CBL” or “LBM” was, to some extent, indebted to the project. In this section, I trace some of the more important outgrowths of the landmark MBL project.

The three-year MBL project was our only funding specifically for developing probeware technology. Granting agencies try to avoid repetitive grants and are hesitant to fund hardware and software development. Consequently, all future advances in the technology had to be funded by industry or incorporated into projects with other goals.

THE UNIVERSAL LAB INTERFACE

In the mid-1980s, the dominance of Apple IIs was slipping. The Macintosh, Atari, Commodore, IBM, and other computers were all vying for the school market. Instead of designing hardware for each, we decided to return to our earlier idea of interfacing through the serial port present in all computers. By this time, inexpensive microcomputer chips were available that were used to give intelligence to printers, hard drives and other peripherals. It seemed reasonable to do the same for a serial lab interface.

These new chips were inexpensive versions of the processors used in microcomputers packaged with pared-down versions of some or all of the other building blocks typically found in a computer: memory, inputs, outputs, and, support circuits. For instance, the Intel 8048 was similar to the 8080 chip plus some memory and a number of digital lines that can be used for inputs or outputs. With only a bit of additional electronics, such a chip is a complete, inexpensive computer capable of adding intelligence to any device.

An intelligent lab interface could take over much of the low-level processing previously done on the main computer. It could also buffer data gathered at high speed and send it on through the lower speed serial line. At the end of the MBL project, we started work on this, but ran out of funds. Pricilla Laws picked up the idea and, in collaboration with David Vernier, created an 8048-powered interface known as the Universal Lab Interface, or ULI. This was the first of many such microprocessor based universal lab interfaces.

THE COMPUTER AS LAB PARTNER PROJECT

In the mid-1980s Marcia Linn and her students began an important, decade-long study called the Computer as Lab Partner (CLP) project. With an initial grant from Barbara Bowen at Apple Computers, she focused on teaching heat and temperature in a middle school physical science course. With the help of John Layman, on sabbatical from the University of Maryland, she used our Red Box, pulser, and software.

The CLP project adopted the “design experiment” approach, in which they developed, taught, and modified their approach every semester for almost ten years. As time went on, they made increasing use of simulations and other instructional strategies to get students to reflect on what they observed. Each cycle they measured student performance, and it improved every time. For instance, the data on student understanding of the distinction between heat and temperature is shown in Figure 2.

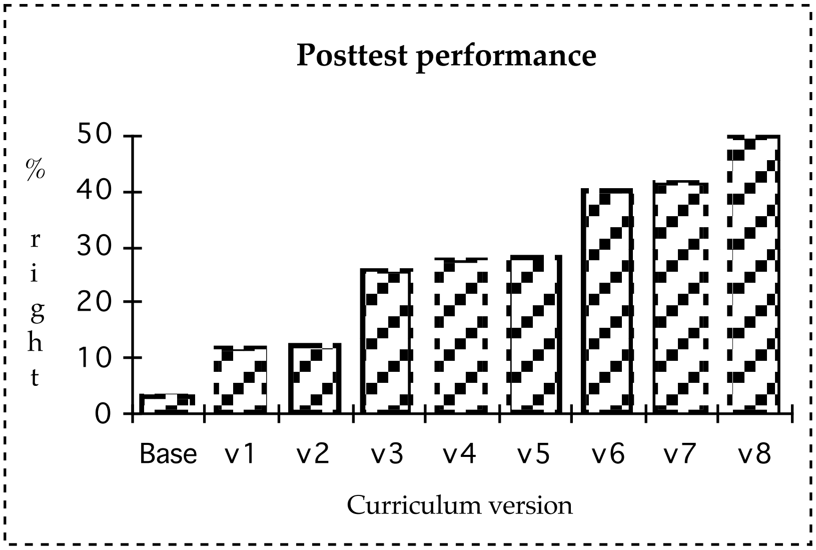

Figure 2. Improvement of student performance on a problem over eight versions of the curriculum. *The problem requires students to distinguish accurately between heat and temperature. The later versions of the curriculum had different instructional goals and are not shown. (Adapted from Linn, et al, 1990.)*

There were strong similarities between all versions of the CLP curricula—they were all lab-oriented, involved the same teacher, used computers in the lab, and devoted an entire semester to heat and temperature. It is important to note that changes in the curriculum caused large changes in student learning *even though there were strong superficial similarities in all treatments*. This shows how important the curriculum design is and that there can be no such thing as “proof” of the value any technology like probeware that is independent of the curriculum. Conversely, this research demonstrates how a weakness in the curriculum can mask the effect of a perfectly good use of technology, as demonstrated by the ETC study.

IBM AND THE PERSONAL SCIENCE LAB

One day when I demonstrated the rolling can experiment using an Apple II, a tall man in a three-piece suit and cowboy boots announced to me that IBM had to have a probeware product. This chance meeting with Phil Smith led to the development of IBM's Personal Science Lab (PSL), an integrated probeware system now marketed by Team Labs.

With the connivance of his boss, Tom Greaves, Phil committed IBM to develop the PSL before the lumbering IBM decision-making process even knew what had happened. Phil assembled a team to develop an outstanding 8048-based interface that was far more complex and capable than the ULI or any other interface then available. Phil was uncompromising in quality; he wanted the most accurate, fastest, easiest to use, lowest-cost probes possible. He believed that IBM could avoid the "times seven" rule through mass production, large sales, and a personal appeal to "bean counters" within IBM.

The interface was fast and expandable using its own high-speed serial bus. It was strong enough to stand up to the abuse typical of the classroom as Phil used to demonstrate by jumping on the interface box. Connections to it were made using cigarette-box sized cartridges that contained probe-specific electronics and were self-identifying. One goal was to eliminate the need to calibrate probes before using them, a step that baffles beginning students. The PSL probes were either pre-calibrated or had calibration constants stamped on them. Another goal was to maximize the effective range of probes through electronically controlled amplifiers in some of the cartridges.

Each of the PSL probes was a masterpiece of engineering. The motion, rotation, and pH probes were particularly impressive. The motion detector was easy to mount on a table, standard laboratory rods, or hung from a wire. The rotation detector was a smart pulley with very low friction and high angular resolution. The pH probe used a novel field-effect transistor sensitive to pH that made it unusually robust and stable. IBM contracted through CDL to have TERC develop an ambitious software package and a set of student activities. We developed an improved, integrated software package that supported all the probes while offering a wide range of data analysis tools and context-sensitive help.

The resulting PSL package was most impressive. Unfortunately, the PSL did not have the impact it deserved, because IBM made several mistakes. IBM never made a Macintosh version of the PSL, because it hoped to use the PSL to influence school decisions in favor of IBM computers. Since most schools then had more Macintosh than IBM computers, the lack of Macintosh compatibility simply meant schools chose other probeware systems. The second mistake was to think that IBM was immune to the "times seven" rule. In the end, the IBM "bean counters" won and the product had to pay off its huge development costs by charging non-competitive prices. The third mistake was that the product was so ambitious that it took too long to develop, test, and market. Unfortunately, we contributed to these delays because TERC, as a research and development organization, was not set up to undertake speedy, production software development.

INTERNATIONAL EFFORTS

Probeware developed independently in Europe in a number of countries, including the England, Scotland, Holland, Germany, and Italy. In general, European universities take greater responsibility for educational innovations than in the U.S. Consequently most probeware innovation has been university-based, usually coming from physics departments.

One of the most impressive efforts has been led by physicist Ton Ellermiejer at the University of Amsterdam, the Netherlands. He has been dedicated to developing and disseminating probeware for 20 years, first in the Didactics program of the Physics Department and more recently at a special institute that combines educational research from all science departments. It is worth noting that both efforts have been linked science departments, not a school of education.

The result of the more centralized, discipline-based approach to education in Europe has typically been a long-term commitment to change coordinated between technical development, teacher professional development, and curriculum change. In Holland, for instance, after long deliberation, probeware was included in the national curriculum in two places. Then Ton's group developed the requisite hardware and software and sample curriculum material that used those tools. Publishers were invited to write their own materials based on these samples. At the same time, every teacher who would teach this new content was being trained. At the beginning of the year in which the new materials were required, all the teachers were trained, all the classrooms had the requisite hardware and software, and all the student materials provided the needed curriculum support. Logical as this approach seems, it would be revolutionary in the US.

The two sides of the Atlantic began to come together around a series of workshops funded by NATO. In an effort to stimulate trans-Atlantic research, NATO sponsors seminars in all areas of science. In the 1980s, it decided to include technology-enhanced science education as one of the research areas it supported. The result was a meeting on probeware at the University of Pavia in Italy in 1988 organized by Ron Thornton, colleagues at Pavia, and ma. A second workshop was held in 1991 at the University of Amsterdam that Ton and I organized. Both resulted in on-going collaborations and the second produced the only book devoted to probeware (Tinker, 1996).

Ton has continued to refine and develop probeware. Steady government funding, combined with the kind of inspired development of which bright, discipline-based graduate and post-graduate students are capable, has led to the most impressive probeware packages currently available. The Coach Jr. software his group has developed includes support for every major lab interface and all their probes. Also included are extensive analytical tools and a modeling environment that allows students to try to build a model to match data. There is even support for collecting data from video images.

THE LABNET PROJECT

In 1993, we received some much-needed funding from Carnegie Foundation to study the impact of networking on education. The first commercial networking service, the Source, had recently been announced with great fanfare, and we wanted a chance to think about what this might mean to education. We conducted polls of teachers, interviewed educators, and investigated all the networking technologies then available. Unfortunately, just before the funding ran out, the MIT graduate student whom we had contracted to do the research disappeared with all our data. Consequently, although we all had had a good education, we never published the study.

We learned that the text-based conferencing software then available over 1,200 baud modems was probably too limiting for most student applications, but that teachers might be able to profit from the technology, especially for sharing among isolated professionals. These insights led directly to the LabNet project, which was funded in 1995 after kicking around the NSF for 18 months. John King and I were again co-Principal Investigators on the project.

LabNet was originally designed to support physics teachers in their use of probeware. At an initial summer workshop at Tufts, it became clear that the combination of two technologies—probeware and networking—was too challenging for typical physics teachers. Around this time, Dick Ruopp, who had retired from Bank Street, took over the project and shifted the emphasis to using networking to create a community of teachers. The project focus shifted to studying that community. Physics teachers predominated and probeware was a topic of discussion, but not a defining characteristic of the discussions. The project created and studied what became one of the first online virtual communities for teacher professional development. The insights from the project were edited into a book by Dick Ruopp (1993), even though he was confined to bed with ALS. This strand of studies continued for a decade at TERC (Feldman, 2000).

PROBES AND PORTABLE COMPUTERS

STUDENT LEARNING IN CONTEXT

In the late 1980s, Wayne Grant, an educator at Apple Computer, produced “Digital Coyote”, a short video that illustrated the educational potential of portable, wireless computers. Wayne had cobbled together a demonstration that used portable Macintoshes, citizen band radios, and probes. The video shows kids gathering data about a desert environment, sharing their results immediately, and collaborating to try to make sense of their data on the spot. Although these technologies had been envisioned earlier, Wayne’s video had a huge impact because it showed so vividly the possible educational impact of these technologies. “Digital Coyote” and “Rain Forest Classroom”, an update that Wayne produced with better technology, were intended to demonstrate an idea; there was no practical way to implement this idea at the time and the educational ideas shown were enacted just for the filming. Both videos pre-dated Apple’s Newton, the first handheld.

With the advent of the Newton, it appeared feasible to begin classroom trials of the Digital Coyote idea. This concept evolved into the first major project at the Concord Consortium, called Science Learning in Context, or SLiC. The idea of the project was to explore the feasibility of using probeware with portable, wireless computers for student field explorations. Our concept of “field” encompasses anything outside the lab; it could be in the classroom, corridor, bus, home, street, or actually out in a field doing environmental studies.

Wayne continued his involvement with this concept as a member of the SLiC project advisory committee. In partnership with Elliot Solloway and his students, we began assembling probes, wireless, and supporting software for the Newton. The goal was to launch some initial studies of the resulting educational affordances. We wanted to see whether it was actually useful to move outside the classroom for measurements and collaborations, supported by flexible, portable computers.

This project was beset by problems at Apple. The Newton turned out to be too far ahead of its time. The available technology was not quite up to the task, the resulting computer was too bulky, and its critical handwriting recognition software had to be crippled in order to fit into the available memory. Because Apple was loosing money at this time, they would not even give us Newtons for classroom trials; we had to purchase them with grant funds. Worse, Apple could show us fantastic wireless communications that worked with the Newton, but, for legal reasons, could not release this technology for use in our studies. This was a problem bigger than Apple; because of difficulties with the regulators, wireless technology was slowed industry-wide. The wireless probeware that we envisioned when we submitted the proposal, had to be delayed for another project.

Our earliest trials reminded us that computers and interfaces used in the field need to be particularly reliable, robust, and require a minimum of connections. It is far more difficult to fix a problem in the field than in a lab. Even removing a screw to replace a battery is more difficult; you might not have the right screwdriver and you almost certainly do not have a clean table on which to work. Every wire gets tangled and tripped over. Computers and interfaces get wet and are dropped.

We first used Vernier probes and a battery-powered version of their Low Cost Interface (LCI). Elliot’s students wrote software for collecting and displaying data from the probes. Classroom feedback indicated that there were endless problems with the batteries for the interface coming loose and wearing out. To solve this problem, Stephen Bannasch and Walter Lenk came up with a better interface that was functionally like the LCI but did not require a battery.

By this time, single-chip microcomputers had advanced beyond the 8048. The PIC series of microcomputers from Microchip included one version that required very little power and contained an analog-to-digital converter. With some very clever circuitry that derived the needed power from the serial port, we were able to program the PIC to emulate the LCI without needing batteries. This simple change made a huge practical difference in the field.

Within a year of the start of the project, Steve Jobs, newly returned to the helm of a financially imperiled Apple, announced dramatic changes to focus Apple on its core business. Among these changes was the elimination of the Newton. Our friends at Apple, however, told us that a substitute was on its way that was compatible but better for education, so we were not too worried about having a project dependent on a non-existent technology. The substitute was the e-Mate, the first computer designed for education by a major computer company. Rugged, light, and attractive in a green clamshell case, the e-Mate ran the Newton Operating System.

The e-Mate ran against conventional wisdom. It had a half-VGA sized black-and-white screen. It had no hard disk, but substituted flash RAM instead. This means that it could instantly resume whatever it was doing when last used; far more friendly than the endless boot cycle of conventional computers. Eliminating the hard drive reduced power demands, so the battery could last all day, an essential requirement for a student’s personal computer. The e-Mate had built-in a simplified word processor, spreadsheet, and other utilities that were more than adequate for educational uses. In addition to an almost-full-size keyboard, it had a touch-sensitive screen and handwriting recognition. This was the same vilified handwriting recognition software used in the Newton, but no longer hobbled with insufficient memory, so it worked very well. The Newton OS, a brilliant but oddball operating system, was needed because it minimized the amount of expensive flash RAM required. Finally, the e-Mate supported infrared “beaming” that allowed students to share data or other files by simply aiming two computers at each other and pressing a button. While not as flexible as the radio wireless we envisioned, this turned out to be effective at supporting student collaboration in the field.

The e-Mate designers listened to educators and included most of the tool software they requested. Apple was aware that science teachers demanded probeware, so they formed an alliance with Wayne Grant, then at Knowledge Revolution, Inc., Elliot Soloway, and us to adapt the Newton probeware to the e-Mate and market it as “e-Probe”. This was announced along with the first public introduction of the e-Mate. Customers could order the e-Probe directly from Apple as though it was part of the complete package.

We purchased several class-sized lots of the e-Mates, equipped them with probeware, and launched classroom trials in Ann Arbor, Michigan and Mt. Baker, Washington. We also convinced Apple to produce a third video in its series by Wayne Grant. This recorded the field studies of the students at Mt. Baker, finally showing real students with commercial equipment doing the kind of field-based, collaborative learning envisioned in the two previous videos, although still without wireless.

The two field test sites illustrated very different ways to use portable probeware. In Ann Arbor the hardware was used in a middle school science course at Greenhills, a private middle school. A pair of gifted teachers, Chris Gleason and Ann Novak, were in the process of redesigning three years of middle school science using Joe Krajcik's approach to inquiry-based science learning. The e-Mates, equipped with probes for temperature, light level, pH, and dissolved oxygen, allowed them to design a series of problem-based environmental investigations of their local stream. Units in the fall and spring were carefully designed around driving questions and key science content. Student understanding of both the field techniques and the science concepts improved dramatically. One of the most impressive measures was the increase in the sophistication of water pollution concept maps students drew before and after the course. The initial maps were sparse, repetitive, and sometimes wrong. After the year, their maps were extensive, sophisticated, and quite accurate.

The students at Mt. Baker High School were juniors and seniors in an environmental science research course led by another gifted teacher, David Tucker. He organized students into small research teams and encourages each to undertake a long-term project of their own choosing. The e-Mates with their probeware were simply some of the tools he had assembled over the years for these students to use. Some students chose projects that required field measurements and these used the technology as a matter of course, just as they used paper and spectrophotometers, as the need arose. What was important was that the technology retreated into the background, because it was easy to use. The student research was most impressive

Unfortunately, the e-Mate went the way of the Newton. Apple abruptly stopped making it, leaving thousands of educators, Knowledge Revolution, and us high and dry. The e-Mate was too odd and expensive to generate a ground swell of support in terms of educational applications and sales and Apple was too strapped for cash to give it the level of promotion, support, and on-going development it deserved. In a way, the Apple iBook portable is its successor and, in 2000, at about the same price.

Fortunately, we anticipated Apple's decision. The importance of our research was not in the specific technology, but in the idea of using probeware with portable computers. Many of the Apple staff working on the Newton and e-Mates were terminated and ended up at 3-Com working on the Palm, our next platform for handheld probeware.

UBIQUITOUS COMPUTERS

In 1997, I joined with Roy Pea and Barbara Means at SRI International, Marcia Linn at Berkeley, and John Bransford at Vanderbilt, to create a distributed Center for Innovative Learning Technologies (CILT). The major contribution of the Concord Consortium to this effort was to encourage cross-sector collaboration on "ubiquitous computers", that is handhelds using probeware and radio wireless. We wanted to explore the feasibility of using handhelds in education, especially for probeware applications. We felt that they could well be the "equity computer" that could bridge the digital divide. The e-Mate demonstrated that powerful education could be done with pared-down computers. Since the Palm had as much power as the early Macs and far more than the KIMs, we were certain that they could find a place in education. This Center funding allowed us to explore these ideas. Our first steps were to develop "smart probes" for the Palm and to encourage the development commercial probeware for this platform.

Our SLiC experience convinced Stephen Bannasch of the need for smart probes: sensors incorporating a microcomputer. The ideal smart probe would not require any batteries or external power and could plug into a computer to immediately begin collecting data. Calibration data might be stored in the probe, relieving teachers of the problem of matching probes to computers that store their calibration data. As we saw, field-based investigations put a premium on simplicity and reliability. Nothing could be much simpler to use than a battery-less smart probe that could start taking data as soon as it is plugged in.

Stephen and Walter Lenk combined the ultrasonic motion detector with a PIC microcomputer to make our first smart probe for the Palm Computer. Unfortunately, the motion detector draws more power than the Palm's serial port can supply, so we had to put additional batteries in the detector. But the power drain is low, and the batteries last for long times. Figure 3 shows the smart probe mounted in a flashlight case and attached to a Palm Computer. It is most impressive to see your position, velocity, or acceleration in real time as you walk with the probe and computer. Stephen and Walter also used PIC computers to make smart temperature and light probes that did not require batteries.

Figure 3. The smart motion detector *interfaced to a Palm handheld computer. The ultrasonic transducer can be seen mounted in the face of the flashlight case. The PIC microprocessor and other electronics can be seen through the window of the case. The Palm display on the right shows time-graphs of the position (lower trace) and velocity (upper).*

Commercial interest in educational applications of the Palm can be traced to a June, 1999, meeting we organized through CILT with 3-Com to encourage them to devote some effort to the educational market. Our meeting fell on exactly the day that Jeff Hawkins, the Palm designer announced his departure to form Handspring, a competitive handheld. While neither company had any plans to enter the educational market, both were intrigued by the motion detector and eventually began supporting educational applications. At the same time, Wayne Grant created his own company, ImagiWorks, which soon launched a probeware package for the Palm, consisting of a clip-on interface, software, and Vernier probes. The entire package, with Palm computer, cost about the same as other probeware packages that required a computer.

As part of our CILT work, Carolyn Staudt undertook some studies of students using Palm-based probeware at elementary and middle grades. Students in these grade related will to the handhelds and seemed to begin using them quickly and effectively. She reported that second graders had difficulty sharing the handhelds, and their small screens makes them difficult to share between more than two students.

FUTURE DIRECTIONS

It is surprising that probeware is not more widely used in education. There are a number factors that impede its use, including costs, the steep learning curve for teachers, the paucity of evidence for probeware, and the standards. Current and future work needs to be focused on reducing these barriers.

PEDAGOGICA

Probeware software has evolved since its beginnings toward increasingly general software. The first applications, such as the cooling curve program or the heart rate monitor, were short and designed to do single experiments. The trend has been toward increasing generality and universality; one or a few applications that can handle a very large range of experiments. This is valuable, since the ultimate goal is to give every student unfettered power to learn through exploration, using general tools that can be applied in unforeseen ways. Yet, as the power of probeware software has increased, so has the time students and teachers need to invest in learning to use all its functions. This has probably greatly slowed its adoption.

One solution to this problem is to build “scaffolding” into the software. Scaffolds are used to help construct a building, but are removed when the building is complete. In the same way, software scaffolds should be present when students are beginning to construct their understanding, but should fade away when no longer needed. The practical problem with software scaffolds is that they are hard to do well. Software built with scaffolds can easily be too intrusive or too invisible and its prompts can be too specific or too generic. It is a risk to "hard wire" scaffolding into a probeware application, particularly if this is to be done by a programmer who lacks educational expertise. Another strategy is needed.

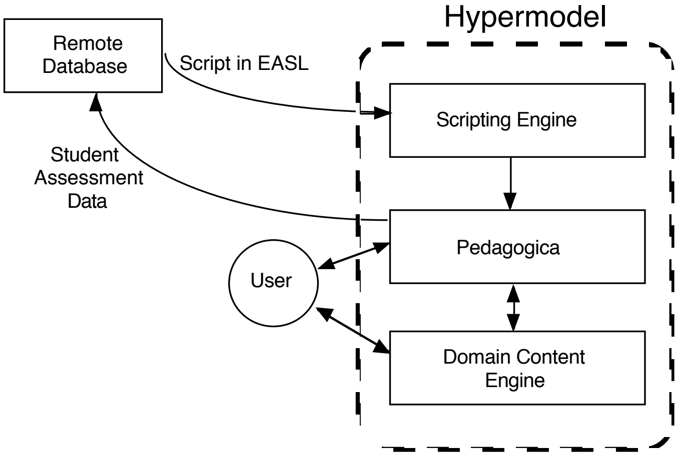

Figure 4. A hypermodel *consists of a tool or model application that contains some domain content such as genetics or probeware. Pedagogica controls the appearance, starting conditions, and available user options for this application. Pedagogica itself is controlled by a script written in EASL that is interpreted by a scripting engine.*

The solution proposed by Paul Horwitz and illustrated in Figure 4, is to separate the pedagogical strategies, such as scaffolding, from the application. He builds "hypermodels" (Horwitz, 2000) that integrate multimedia materials, experimental data, and text with subject domain tools like probeware. Thus, students' actions in the tool environment can trigger the presentation of experimental data or bring up a question. In turn, their answers to questions or manipulations of an experiment can affect the configuration of the tool. Hypermodels are *scriptable* and thus provide a flexible tool for the creation of a wide variety of activities that challenge students to solve problems with our tools and then scaffolding and monitoring their actions. Stored text and graphics can structure a student's investigation of a domain and offer metacognitive prompts as well as links to real world science. Each activity produces a log file of student actions and responses, and thus provides a valuable new tool for embedded assessment and educational research.

Hypermodels comprise three separate software layers: a tool, a scripting layer, and the glue that links them – a program we call "Pedagogica." Thus, in a probeware hypermodel, the tool consists of a general-purpose probeware package. Pedagogica can determine what options are available, how data will be collected and displayed, and what probes are expected. The scripting layer interprets short programs that are written in a simple language called EASL[3] developed by Paul's group at the Concord Consortium. These scripts implement the activities that students interact with, setting up the initial problem, configuring the hypermodel to match the problem, observing and reacting to students' actions, and communicating with them as they work through their investigations. The job of Pedagogica, then, is to communicate between the script and the underlying content engine.

Whereas the hypermodel software is typically resident on each computer in a classroom, the scripts may be located on a central server, either remote or situated within the classroom. This makes it possible to present students with customized learning experiences. For research, this means we can easily manage different treatments within the same classroom. For educators, this means that the activities can be adapted to match individual needs. Using scripts, we can control and limit the options presented to students. Instead of getting lost, we can focus their attention on a particular problem. They can still explore and learn through inquiry, but in a reduced space that is more easily completely explored and understood. We can also prompt students to think about what they are learning and to explore the links to other concepts.

Probeware hypermodels could make the educational use of probes far more practical. Beginning students could use sophisticated software that was 'tamed' by Pedagogica scripts that limit the available options and provide guidance. Suppose, for example, that a teacher wanted to introduce probes by having student measure the temperatures at

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[3] EASL stands for Educational Application Scripting Language.

different places in the classroom. A script to support this might start by posing some challenges to kids and getting them to make some predictions. Then, it might encourage students to sketch the classroom and place temperature measurements onto the appropriate places on the sketch. The software, noting some deviations at nearby places, might ask the students to explain the differences. It might also report to a file for the teacher how many measurements were made, whether they were within expected values, and any comments the student generated. Pedagogica would then move on to additional measurements or whatever the activity designer found useful.

The general-purpose probeware software could have been used for the same activities without Pedagogica. The user, however, would have had to work through numerous menus and made many selections to accomplish the same results. The guidance provided by Pedagogica would have to be supplied by a teacher or read from student notes and no embedded student evaluation would be generated. The combination of easy setup, guidance for inquiry, and embedded assessment provided by a probeware hypermodel should greatly simplify the implementation of probeware.

UNIVERSAL INTERFACES

One possible vision for improved SMET education would involve making probeware a thread throughout the curriculum starting somewhere in grades 2-4. Elementary students would actually be introduced to graphs through hands-on experiences with real-time graphs. As a result of these early experiences with concrete variables like temperature and speed, by middle grades students would be comfortable with the idea of probeware and could use probes as a way to understand more abstract variables such as heat flow, magnetism, and nuclear radiation. As their comfort with instrumentation increases, so would their ability to design and carry out their own investigations. If students had access to John King's shoebox of sensors and sufficiently flexible software, the range and sophistication of the experiments students could undertake would be most impressive. One of the problems with many student projects is that students can come up with perfectly good questions that involve measurements that are difficult or impossible with the resources in a typical classroom: the vibration of a SuperBall™, the speed of a falling tree, the amount of arsenic in drinking water, the temperature variations in a automobile engine, the level of salts in a stream after a storm.

A teacher attempting to equip a lab to accommodate such a range of measurements would face a huge cost problem using current hardware. Commercial probes cost from $30 to $200 and a dozen or more might be needed to support an entire year of science labs or to give students the flexibility to design a wide range of experiments. This means that probes needed by one lab group of 3-4 students can cost as much as a desktop computer and the combination can be prohibitive.

The solution is to have students build their own probes and use them with inexpensive handheld computers. If it were possible to use student-constructed probes, the costs of supporting open-ended projects would be far less and student options would be even greater. Even if each student decided their project needed a multiple temperature sensors, there would be no shortage of probes if students could easily make their own. Student probe-making would also save costs and give student valuable experience in design, electronics, and experimentation.

Probe construction is often a very involved process, requiring some electronic signal processing circuits to match the sensor output to a general-purpose input circuit. One sensor, for instance, might generate an output that changes from 100 KΩ to 1 MΩ over a reasonable range of inputs. This needs to be matched to a converter that has a range from 0 V to 5 V, requiring a resistance-to-voltage amplifier with just the right amplification and offset. This is far beyond the knowledge of most teachers and the patience of most students.

We have developed a new smart interface that solves many of these problems. The heart of the interface is an inexpensive 24-bit analog-to-digital converter. This ADC divides its 3-volt input range into 2^{24} or about 16 million equal steps of 0.2 μV each! This is far more accuracy that almost any imaginable student project will need. The value of this incredible accuracy is that most of it can be wasted while still giving satisfactory results. This profligate use of accuracy simplifies or eliminates the need for signal processing electronics. The interface connects to the serial port found in most handheld and desktop computers[4]. It also has a 10-bit converter that can be used when larger, fast signals need to be captured.

To demonstrate the importance of the 24-bit converter, consider using a thermocouple for temperature measurements. A thermocouple is nothing but two wires made of different metals, such as iron and copper. A small voltage is

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[4] To accommodate the computers that have abandoned the serial input in favor of USB, our interface works with inexpensive USB-serial converters. As USB becomes more common, it will be easy to make a USB version of our interface.

generated where they join and this voltage depends on the temperature of the junction, varying by about 60 microvolts per degree. As described in the cooling curve experiment, one typically needs to amplify this signal before converting it to a digital value. But, a thermocouple can be connected directly to the 24-bit ADC with no amplifier. Over the entire range from freezing to boiling, the thermocouple might only changes by 0.006 volts, less than 0.3% of the range of the ADC. This means that we are throwing away 99.7% of the range of the converter. But within that narrow range, the 24-bit converter can still resolve the temperature to 0.03 C, more accuracy than most projects will ever need. The resulting temperature sensor is very handy, too. Because it is easily replaced, it doesn't have to be protected against rough handling. Two very thin wires can be used for the junction, so it can respond quickly to changes in temperature, even in air. This lets students sense tiny, fast temperature changes that commercial sensors, with their sturdy, student-proof housings, cannot. One experiment we have developed involves embedding the junction in a dab of putty and then hitting the putty with a hammer. All the kinetic energy of the hammer goes into heating the putty and the resulting temperature jump can be easily measured. One would never consider abusing a $100 commercial sensor this way!

A large number of sensors can be directly wired to this 24-bit converter. One of our favorite sensors is a linear Hall-effect magnetic field detector. This has three leads: power, ground, and signal. The signal can be fed directly to the ADC and indicates the strength of a component of the magnetic field through the detector. The ADC can detect the earth's magnetic field or the field from a permanent magnet. In addition to exploring magnetism, the sensitivity of the sensor allows it to be used to detect all kinds of things. We have, for instance, placed the magnet on a spring. This becomes a force sensor, since a force applied to the spring generates a motion of the magnet that the Hall effect sensor detects. A number of light, pressure, and position sensors are as just as simple to connect and can be used in many different contexts. With a half-dozen such sensors, no more than three connections, and a collection of common supplies like springs, light bulbs, and hot glue, students would have the instrumentation needed to record almost anything. The 24-bit converter, a few sensors, common hardware, a handheld computer, and some ingenuity would be everything needed to provide instrumentation that would enhance a wide range of laboratory experiences at most grades. The costs might be one-tenth the cost of commercial probeware packages used with a desktop computer.

To take advantage fully of this capacity for student inquiry, a spirit of intrepid exploration needs to be established. This is difficult for teachers who are inexperienced in science inquiry in general and electronics in particular. Can we prepare teachers to support a bit of interfacing and to appreciate the value of the open-ended experimentation that this would enable? Electronics, even the tiny bit needed to attach a sensor to an interface, can be a serious obstacle. Teachers worry that an error could ruin expensive equipment, that something will go inexplicably wrong, or that students will ask difficult questions.

Online courses and teacher forums can go a long way to providing teachers with the support they need to use inexpensive probeware well. Interactive online video case studies are a particularly powerful strategy. Teachers can observe expert teachers using the technology in real classrooms and then break into the video to see related lesson plans, standards, commentary, or background science. The video can also provide detailed views of critical wiring or experiment configurations. With such detailed assistance, teachers can have success in the classroom. It only takes some initial successful experiences and some general ideas about how the interface works for most teachers to gain the knowledge and confidence they need to generalize this approach throughout their teaching.

OBSERVATIONS

The history of probeware makes it clear that an ongoing efforts are required to move an innovation like probeware from research to practice. It is not sufficient to simply point out to educators that probeware is a good idea, even when backed by prestigious educators and research. The difficulty of reproducing educational research means that wide-scale adoption requires continuous dissemination; every teacher needs to be convinced of the value of something like probeware in his or her own classroom. This is why we have focused our dissemination efforts outside the traditional academic paradigm of peer-reviewed papers. Newsletters, articles in the educational press, talks, and workshops help convince teachers, not academic papers.

Many unsung heroes and heroines have helped with this dissemination effort. In particular, the vendors have played a major dissemination role, not only by creating, manufacturing, distributing, and supporting some outstanding products, but also in educating users and potential customers about the value of probeware. In addition, teachers, university faculty, and trainers have helped with dissemination by creating and delivering countless numbers of workshops, lectures, and courses on probeware.

Probeware needs continuous innovation because technology is continuing to change and probeware technology needs to be improved as computers and networks evolve. The comprehensive probeware packages of the early 1990’s would not have been feasible on earlier computers. An inexpensive 24-bit analog-to-digital converter was out of the question five years ago. Tomorrow’s network-delivered hypermodels could not have been imagined a decade earlier.

Educational innovations depend on these technological advances, but considerable work and not a few missteps are required before they can result in improved classroom practice. Our work has required collaborations between hardware and software experts who are familiar with the advances in the technologies, and educators and subject matter experts who can translate new technological capacities into better teaching and learning. It is noteworthy that these kinds of collaborations have not taken root in most U.S. universities. Academic research in the social sciences in general, and in education in particular, tends to be dominated by individual faculty members. Nonprofits like TERC and the Concord Consortium have shown greater ability to assemble and utilize the diverse skills needed to produce advances in educational technologies like probeware.

It has proven extremely difficult to find funding for these collaborations. Technological innovation is expensive because it involves highly trained hardware and software experts, fabrication and testing, and careful quality assurance procedures. Most funding for educational research and development assumes that the technology has already been developed; that the research questions arise from the implementation of existing hardware and software. As a result, our technological innovations have often been “bootlegged”; not even described in proposals or briefly mentioned as adaptations or modifications. We have made advances in the technology by winning several overlapping grants and then assigning a small amount of technological development to each. This is, of course, frustrating, perilous, and inefficient. Educational funders need to provide support for the development of innovative combinations of new technologies, learning strategies, and educational content with the expectation that the resulting collaborations will take place outside schools or universities, but with meaningful inputs from both.

The future decade or two promises continuous improvements in the underlying technologies. High-speed wireless networking based on high-frequency cellular technologies will become powerful and almost free, computers will become smaller, faster, and more flexible, and bio-sensors and other sensor developments will increase the range of inputs that can be measured accurately and inexpensively. We will get smarter about how students learn and how to build software that exploits this knowledge. These developments have the capacity to substantially improve math, science, engineering, and technology education, if we can combine all these developments into effective curricula and then convince educators to implement them. If this happens, the next generation of learners will have access to instrumentation that was only recently confined to advanced science researchers. With these tools, tomorrow’s students will be able to learn through guided exploration at a level of detail and sophistication that will greatly increase their interest, experiences, and retention.

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