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Editor's note: The development of probeware—electronic sensors connected to a desktop computer, calculator, or handheld computer, together with supporting software—has revolutionized the conduct of science laboratory instruction and permitted students to engage in true inquiry. Part I of this two-part article offers a summary of educational research findings showing the advantages of using such sensors. Part II, by Nüsret Hisim (p. 38), offers a range of practical suggestions for using probes in laboratory teaching across the sciences.

LOGY

in the Lab

Part I: What research says about using probeware in the science classroom

Mark Millar

Many varieties of data acquisition systems are now available for science classrooms. Most systems consist of a range of sensors—typically called *probeware*—connected to an interface unit usually described as a *datalogger* due to its capacity to record data from these sensors. Although some systems operate independently, most units connect to a desktop computer, handheld computer, or calculator for at least some of the time to allow data to be viewed and manipulated in a range of ways. Some manufacturers produce standalone units with their own data output screens, which do not rely on a computer connection.

Although most early sensors were designed for use in physical science classes, systems are also now available for data collection in chemistry, biology, and Earth sciences. Permanently mounted systems, such as weather stations and other environmental monitors, gather a continuous stream of data over long periods of time. Whatever the physical design of the system, they all enable students to use technology to collect and view experimental data more quickly and easily than is possible without them.

Technology-enhanced environments

Data acquisition systems can be used to create constructivist, inquiry-based classroom environments in which students collaborate with one another in groups and the teacher acts as a facilitator and guide (Jonassen 2000). Research shows that the use of technology can both encourage the development of constructivist environments in the classroom and support learning once that atmosphere has been established. "Technology-enhanced student learning environments create contexts within which knowledge and skill are authentically anchored . . . They afford opportunities to seek rather than comply, to experiment rather than accept, to evaluate rather than accumulate, and to interpret rather than to adopt" (Hannafin and Land 1997, p. 9).

With this type of technology, students are guided into thinking for themselves in ways that would be difficult in the noncomputer-based classroom. As students work with data acquisition systems, they are not merely presented with a series of facts in a detached situation. The clear, colorful displays represent authentic, real-time data coming from the chosen sensors. Students must then think deeply about the relationship between these readings and the actual event. Software systems and hardware probes permit students to follow independent, personally relevant paths as they conduct investigations, aided by rich and flexible graphing capabilities.

Inquiry-based activities

According to Edelson, Gordin, and Pea (1999), students should learn how to conduct investigations the way scientists themselves conduct investigations. This process is led by questions and is often open-ended (1999). Research has consistently shown that students reap considerable benefits when the teaching and learning of science takes place in this manner, not only in the area of understanding scientific concepts but also in acquiring scientific skills. Students who search for and encounter scientific concepts in an authentic and meaningful context gain an improved understanding of those concepts. Students who learn science by inquiry methods have the opportunity to develop and build a range of investigative and thinking skills such as posing research questions, analyzing, and communicating (Edelson, Gordin, and Pea 1999, pp. 393–394). Perhaps most striking are the contributions that computer and networking technologies can make to the success and effectiveness of inquiry-based learning. The following contributions have been identified:

- Enhancing interest and motivation;
- Providing access to information;
- Allowing active, manipulable representations;
- Structuring the process with tactical and strategic support;
- Diagnosing and correcting errors; and
- Managing complexity and aiding production (Blumenfeld et al. 1991; Owens, Hester, and Teale 2002).

The use of data acquisition systems in science instruction helps improve and sustain student engagement. Students are also enabled to establish quantitative and qualitative relationships and conclusions without the distraction of complicated manual data collection. The structure of the user environment, the breadth of data available from the sensors, and the multiplicity of ways of analyzing and manipulating the data allow teachers and students to pose a range of research questions, which may then be investigated in depth.

Teachers may be able to give students increased freedom in deciding what factors to investigate while remaining confident that such investigations will tie in closely with curriculum targets. The ability to export data to a spreadsheet, an option offered by many systems, gives any investigation or inquiry the possibility of being truly open-ended, limited only by student imagination and ability and the class time available. Hence, the use of computer-aided data acquisition can provide students with the opportunity to improve their grasp of particular scientific concepts as well as their investigative and research skills as they learn by inquiry in a contextually rich environment.

Supporting critical thinking

Many overlapping definitions and descriptions of critical thinking and higher-order thinking skills exist. What exactly are we seeking to achieve with students? According to the Iowa Integrated Thinking Model (IDE 1989), critical thinking involves three general skills—evaluating, analyzing, and connecting. The process of evaluation includes the ability to assess information, determine criteria, and prioritize. Analyzing incorporates the identification of main ideas and assumptions. Connecting refers to the skills of comparing and contrasting, logical thinking, deductive and inductive referral, as well as identifying causal relationships. As students discuss the data they have collected and the relationships they observe, they will have the opportunity to engage their minds and practice these skills.

In technology-rich classrooms, students tend to be considered as thinkers rather than vessels to be filled with "knowledge" (Thoms and Junaid 1997). When students are allowed to reach conclusions independently and gain opportunities to investigate and manipulate particular physical systems, as well as to apply graphing and numerical skills to an actual event, they are much more likely to develop and retain their own valid conclusions. The use of well-designed software tools helps students to learn to deepen their engagement with information, particularly in the area of analysis and scientific inquiry (Roschelle et al. 2000). Jonassen coined the term *mindtools* to describe software that is effective for this purpose, recognizing that such computer applications "require students to think in meaningful ways in order to use the application to represent what they know" (2000, p. 4). In this respect, computer-based data acquisition systems have the potential to be mindtools. As students begin to collect and record real-time data from the system and progress to interpreting and manipulating data using the software or external spreadsheets or databases, they will necessarily engage higher-order thinking skills. During a well-constructed laboratory session, students will evaluate the physical system under investigation as they analyze the data and its relationship to various external factors and connect this information together as they work through their projects.

Microcomputer-based laboratories

The use of data acquisition systems transforms the science laboratory into what has been termed a *microcomputer-based laboratory (MBL)*. Such data acquisition systems support instruction that involves the measurement of physical quantities by probes or sensors attached to a computer, enabling that physical quantity to be studied, plotted, and analyzed in real time. Such instruction can significantly improve students' ability to understand and interpret graphs (Linn, Layman, and Nachmias 1987; Adams and Shrum 1990; Svec 1995).

Thornton and Sokoloff (1990) list ways in which these instructional approaches appear to be significant in aiding student learning:

- The tools allow student-directed exploration but free students from much of the time-consuming repetition associated with data collection and display.
- The data can be plotted in graphical form in real time so that students receive immediate feedback and can view the data in an understandable form. Students understand the graphs better because the graphs are produced while the event is actually occurring, rather than being constructed after the fact.
- Because data are quickly taken and displayed, students can easily examine the consequences of a large number of changes in experimental conditions. Students spend a large portion of their laboratory time observing physical phenomena and interpreting, discussing, and analyzing data.
- Students are able to focus on the investigation of many different physical phenomena without spending a large amount of time learning to use complicated tools.

- The tools dictate neither the phenomena to be investigated, the steps of the investigation, nor the level or sophistication of the curriculum. Thus, a wide range of students from elementary to university level are able to use this same set of tools to investigate the physical world (1990, p. 859).

Carrying out quantitative studies of physical phenomena can, at times, be time-consuming and likely to obscure the aims of such investigations. However, because data can now be acquired almost at the touch of a button, students can select the range or type of data to be plotted, quickly repeat or modify experiments, and can even compare current data sets with those obtained during a previous lesson, something which is thought to be critical to the success of such instruction (Brasell 1987a, 1987b).

Central to all of this is the link students are encouraged to establish between actual events and the data obtained, thus enabling students to understand more clearly what they are measuring. The wide variety of data that such systems are capable of collecting, together with the range of graphing options, and even the ability to export data to an external spreadsheet, means that differentiation in terms of age, ability, special needs, or focus is a key feature of this form of MBL, making it an accessible and useful educational tool at all levels.

Supporting student learning

Computer-based data acquisition systems contribute to the establishment of a technologically-enhanced student-learning environment, supporting student learning by placing an emphasis on student-centered inquiry and collaboration. The systems provide opportunities for inquiry-based teaching and learning, thus increasing student motivation and engagement, improving students' understanding of key scientific concepts, and encouraging the development of investigative and research skills. Data acquisition systems have been shown to encourage the development of higher-order thinking skills such as critical thinking, and there is strong evidence to suggest that presenting material in this way enables students to achieve more concept mastery than if they were taught only using text-based resources (Frear and Hirschbull 1999; Mayer et al. 1995; Mayer and Gallini 1990). Such instruction can significantly improve students' ability to understand and interpret data and graphs and can make a valuable and unique contribution to students' education. ■

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Technology in the Lab

Part II: Practical suggestions for using probeware in the science classroom

Nüsret Hisim

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Probeware is increasingly being implemented in science classrooms because it is less expensive than it used to be and improvements in hardware and software have made it more accessible to students and teachers. Many probes or sensors can now simply be connected to a computer, calculator, or other handheld device, and will immediately begin to collect data once connected.

Inquiry experiments allow students to apply what they know (or think they know) to topics of interest in a more unstructured manner. Using probeware for inquiry labs has a number of advantages. First of all, most students enjoy working with computers and already come to the laboratory with at least a basic knowledge about computers. Probeware allows students to quickly gather data and examine graphical and numerical representations of the results. Probeware also allows students to gather more accurate data and, in some cases, make measurements that could not be made with manual instruments. With probeware, students can investigate experiments that take place over extended time periods and that would be tedious to monitor by direct observation and manual instruments.

This article focuses on probeware activities I have used in the classroom and worked on with individual students as science fair projects. By being able to collect, analyze, and adjust data so quickly and easily with probeware, students can

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investigate science topics of interest to them in an exciting manner.

Testing batteries

Students today are surrounded by handheld devices, such as cell phones, music players, and games. Batteries are a big part of their lives. One way to study batteries is by having students conduct the following investigations:

- Which brand of battery is best? Are more expensive batteries really worth the cost?
- Are rechargeable batteries as good as one-use batteries?
- How much does the capacity of a rechargeable battery drop off after several uses?
- How do various types of batteries (e.g., nickel-cadmium, alkaline, nickel-metal hydride, lithium ion) compare?
- What role does temperature play in battery life?
- What batteries are best for light loads (e.g., music players, cell phone) and which are best for high-power use (e.g, toys with motors, drills)?

Students can investigate the questions above by using voltage probes available with most probeware systems to monitor the battery status of any electrical device during use. This is easiest if the device uses replaceable, individual batteries (AAA, AA, C, or D cells). To begin the investigation, the teacher or student should simply clip one lead of the voltage probe to the negative end of the first battery and the other lead to the positive lead of the last battery and read the battery-pack voltage. Note that the input impedance of any probeware system is relatively high, so the voltage probes will not draw any significant current that would affect the experimental results.

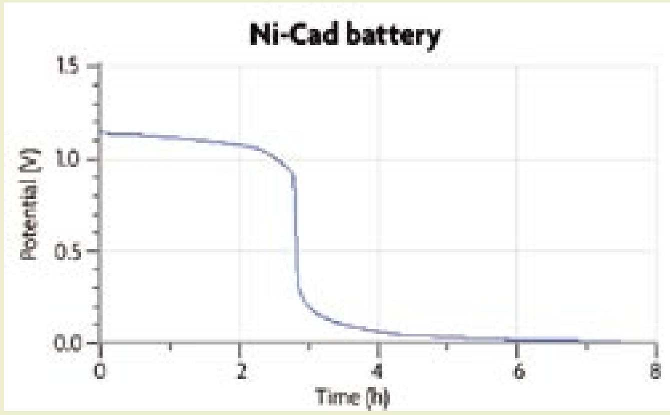
These investigations can take a long time; doing this experiment without some system for automatically plotting the voltage versus time can be boring for students. Most software can now be set to collect and plot data at nearly any interval of time and for as long as desired. Depending on the load, some of these batteries can last a long time. For example, a CD player may run for a number of hours on a fresh set of alkaline batteries. The software would need to be set up to record the voltage, for example, every 15 minutes for 10 hours. Part of the investigation could include determining the limits. Projects of this type might need to be set up and left undisturbed for a period of time. However, the computer or calculator does not have to be committed to the experiment for this long. Some interface devices can be set up to monitor and collect data remotely so that once the experiment is running, the computer, calculator, or handheld device can be disconnected.

Students may discover in inquiry investigations on battery discharge that different types of batteries have different shapes to their discharge curves (Figure 1). Students may also be surprised that the different battery types have different initial (fully charged) voltages.

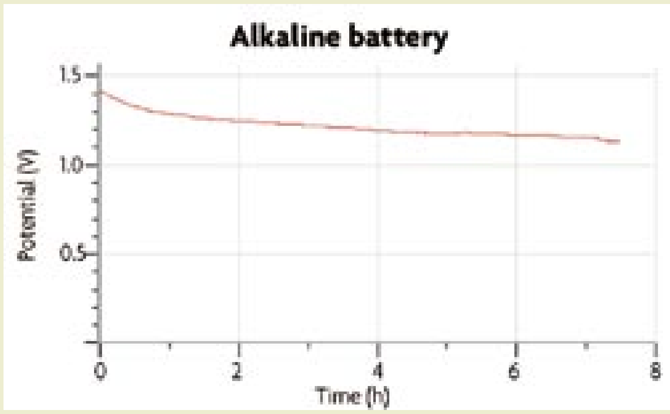
FIGURE 1

Sample discharge curves.

Ni-Cad battery discharge



Alkaline battery discharge



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Friction studies

A standard physical science lab, which is often conducted as a "guided inquiry," involves investigating friction as an object is pulled along a horizontal surface. There are two ways to conduct this lab. One way is by pulling a rectangular block using string attached to a screw eye along a table and measuring the friction force. Rotating the block will vary the surface area between the block and the table. The *normal* force (force pressing the two surfaces together) can be varied by adding weight to the block. The surfaces can be varied by changing the contact surface of either the block or the table. Adding sandpaper to one side of the block can provide an additional variable of interest.

Another way of conducting the lab is by using shoes brought in by students. The variables are harder to control in this version of the lab, but students do enjoy bringing in shoes with different surface materials and treads. Testing various athletic shoes for different sports provides interesting inquiry activities, and can lead to discussions and investigations about the differing importance of friction in various sports.

No matter how the investigation is conducted, students can use probeware to monitor the frictional force needed to pull on the object, initially at rest, until it moves at a slow, steady rate. The probeware can create a graph of force versus time (Figure 2). Using probeware in this case is better than using the traditional spring scale. With a spring scale, the force reading bounces around considerably while the object is being pulled. The same variation in the force readings occurs with a probeware system, but students can examine the graph of force versus time and use the analysis features of the software to calculate the average force.

Most graphs made by students will resemble Figure 2. Hopefully students will notice that force increases and then decreases slightly in a typical experimental run. This offers a great introduction to the concepts of static and dynamic friction and can lead to discussions about automotive braking and driving on snow and ice.

Testing UV protection

Probeware can also be used to study the relationship between ultraviolet (UV) light and the materials designed to block it. Although this investigation can also be done with commercially available UV beads (see "To Tan or Not to Tan?" in the September 2005 issue of *The Science Teacher*), the possibilities for inquiry investigations increased dramatically once relatively inexpensive UV sensors became available for use with probeware systems. Students may find the following inquiry investigations interesting, particularly because the results have health implications:

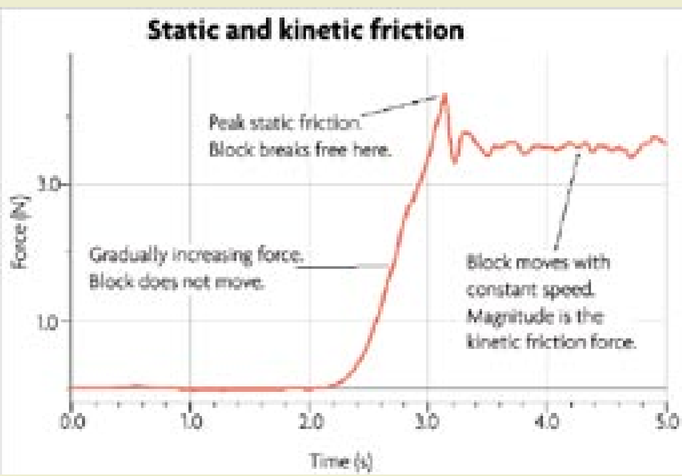
- Can you get a tan or sunburn through a glass window?
- Which sunglasses really block UV? Are the expensive ones that much better?
- Are the Sunburn Protection Factor (SPF) numbers on sunscreen packaging really meaningful?
- Is there a limit to how protective SPF really is? In other words, is SPF 45 three times as effective in blocking UV light than SPF 15?
- How important is it that the sunscreen be applied in a thick layer?

These investigations can be conducted on a sunny day outside or at an open window. Students can measure the percentage reduction in UV intensity as they hold the various objects between the sun and the UV sensor. Unlike UV beads, the measurements can be made instantly, allowing more time for inquiry. Of course, students must not look directly at the sun when performing these experiments. Artificial UV sources may also be used, but students' eyes should be protected if such sources are brought into a classroom.

Another variation of these inquiry labs involves sunscreens. Most plastic-wrap materials used for storing food in the kitchen or refrigerator do not absorb much UV. Students can investigate this assertion with simple tests. Then, if students are curious about whether sunscreen really works as advertised, they can smear sunscreen on the plastic wrap and then hold the plastic wrap between the UV sensor and the sun to see the reduction in UV. Students can then take the investigation further by looking at whether a sunscreen of SPF 4 really cuts the UV to one-fourth the initial intensity. Some probeware is designed specifically for UVA and UVB radiation, so students can extend the

FIGURE 2

Typical force versus time graph for an object pulled from rest.



investigations to find differences in the way these two wavelength ranges are transmitted.

Investigating intermolecular forces

To compare the strength of van der Waals forces and hydrogen bonding, students can monitor the change in temperature as they evaporate small quantities of liquids from the tips of temperature probes. Students then compare the shapes of the curves to the molecular mass and structure of the compounds.

Before long, students will start inquiring about other compounds. I ask students to predict how the temperature curve will compare to the compounds they have already experimented with. This simple activity is made more meaningful and interesting by using probeware; it is extremely tedious when using a thermometer and manually graphing the data.

Inquiry competitions

One great way to involve students in inquiry-style investigations is by organizing contests that use probeware. The teacher presents a challenge, with specific rules and limitations, and students try to use their scientific knowledge and creative talents to come up with a winning entry. The key is for the teacher to carefully construct the ground rules to provide a challenging, interesting contest. (Safety note: Students must wear safety goggles and follow standard safety protocols during all of the contests.) Contest examples include:

- *Insulation contest:* Students insulate a bottle of hot water to try to minimize the heat loss. They then compare rates of cooling using a temperature probe.
- *Air pressure contest:* Students are challenged to come up with a way to produce the highest pressure possible in a clean, dry, plastic soft drink bottle that they will connect to a probeware pressure sensor. Rules must be established in advance. Students should be told that they can only use parts of their bodies to change the pressure in the bottle. For example, they can squeeze, rub, or even step on the bottle. The winner has to be able to show the teacher a graph with the highest sustained pressure (highest pressure graphed for 10 seconds).
- *Freezing point depression contest:* Students are challenged to produce the lowest temperature possible using water, ice, and a salt. What salt is best? What concentration is best?
- *Bridge-building contest:* This contest, using balsa wood, toothpicks, or other materials, has been around for years, but probeware improves it. The bridges are tested (to destruction) using a force sensor connected to a computer to graph force versus time. The highest peak force wins the contest. It is a great spectator sport.
- *Solution combination:* Students are given two solutions that react exothermically when mixed. My students, for example, have conducted this experiment with equimolar solutions of NaOCl and $Na_2S_2O_3$ (0.5 M solutions of each). Students are challenged to produce the largest temperature increase they can. They cannot increase the concentration of the solutions, but only adjust the ratio of the two. The winner is the student who combines the solutions in the correct stoichiometric ratio.
- *Packing contest:* Students are challenged to pack an object with a probeware accelerometer in a specific-sized protective container. The objects are dropped from a specified height and the entry with the lowest peak acceleration wins. This is better than the traditional "egg drop contest," because it is quantitative and there is less to clean up.

My favorite inquiry lab

My favorite type of inquiry lab occurs when students choose their own topics to investigate. Throughout the school year, students are bound to ask interesting questions. They might question how something works or why something is done the way it is done, or which product is best to use. Many of these questions provide the seed for great inquiry labs, especially when a motivated student wants to learn more about the topic at hand. Sometimes the question will be interesting to enough of the class to spark a classwide investigation. If probeware is used throughout the year, students will be comfortable enough with it to suggest using it in their own investigations.

The beauty of the current state of educational science technology is that authentic technology is now used in the high school classroom. Using this technology in the classroom has never been easier or more cost-effective. Students can get involved in science in much the same way professional scientists do. Exciting new devices are being developed and adapted every day. The challenge is to continue bringing this technology to our students, because it offers a marvelous way to increase enthusiasm in our classrooms.

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