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Using Data-Collection Devices to Enhance Students' Understanding

While working with high school students at a Mathematics, Physics, and Advanced Technology Exploration Day, we observed an activity in which students tried to reproduce a distance-time graph by walking. They used a Calculator-Based Ranger (CBR) to collect data about their distance from a motion detector and to generate a distance-time graph in real time. During the activity, the students clearly did not understand the distance information that the given graph was conveying. See **figure 1.** Instead of moving back and forth along a straight line to produce a graph that matched the distance-time information given, students typically walked in a path that resembled the shape of the original graph. Some walked completely out of the probe's detecting range, as shown in **figure 2.**

Students typically walked in a path that resembled the shape of the original graph

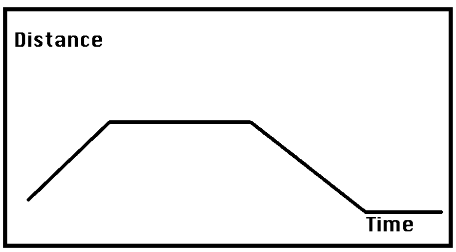

Fig. 1
Distance-time graph for student investigation

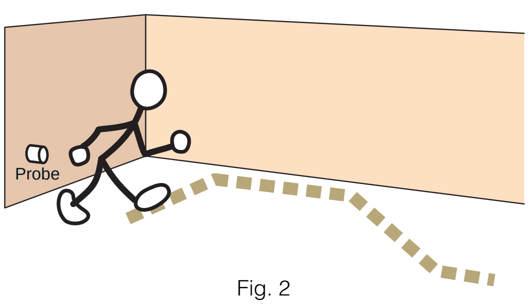

Fig. 2
Path of walker

These students were demonstrating a common misconception about motion and distance, graph-shape-and-path-of-motion confusion (Goldberg and Anderson 1989; McDermott, Rosenquist, and van Zee 1987). They thought that the graph should look like the physical event being observed.

Although researchers agree that studying graphs can lead to a deeper understanding of physical concepts (Mokros and Tinker 1987; Brasell 1987a, 1987b; Linn 1987; Goldberg and Anderson 1989; and McDermott, Rosenquist, and van Zee 1987), students often have problems with graphing and modeling (Dunham and Osborne 1991; Leinhardt, Zaslavsky, and Stein 1990; Goldberg and Anderson 1989). From research, we identified several areas of difficulties:

- Connecting graphs with physical concepts
- Connecting graphs with the real world
- Transitioning between graphs and physical events
- Building graphical concepts through student discourse

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In the presence of data-collection devices, these four areas can interact with one another to encourage graphical understanding. Such devices help develop graphical meaning through interactions among the student, the technology, the physical situation, and the interviewer, according to Nemirovsky, Tierney, and Wright (1998). Despite misconceptions—or alternative conceptions—about graphs that were revealed by students' initial experiences with data collection, repeated activities with the devices can improve students' understanding about physical phenomena (Nemirovsky, Tierney, and Wright 1998; Hale 2000; Monk and Nemirovsky 1994; Thornton and Sokoloff 1990; Brasell 1987a, 1987b; Beichner 1990).

This article explores the extent to which graphing technology coupled with data-collection devices can benefit mathematics and science classrooms. Before we continue with an examination of the research, we give a brief description of these devices.

DATA-COLLECTION DEVICES

Microcomputer-Based Laboratory (MBL), Calculator-Based Laboratory (CBL), and Calculator-Based Ranger (CBR) are devices that collect data with various probes and then store the data into a computer or calculator. The data can be analyzed and displayed in different formats, and the student can graph as data are collected or at a later time. **Figure 3** shows the setup of a CBL device to collect voltage data for a decaying capacitor over time.

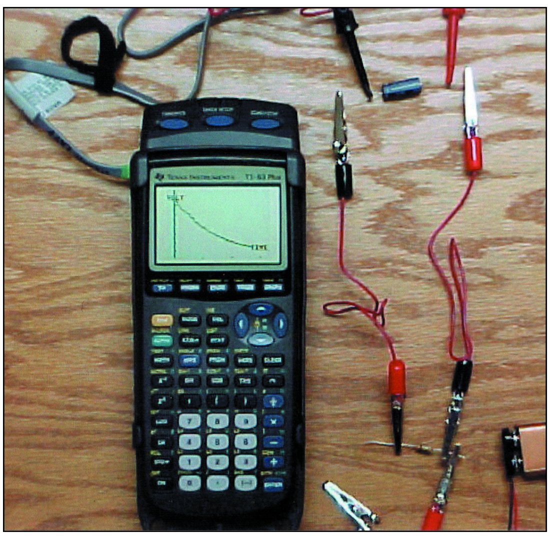

Fig. 3
Capacitor-decay setup with CBL2

Early forms of data-collection devices were expensive and were tied exclusively to computers. However, their increased availability and decreased cost, coupled with probes for graphing calculators rather than computers, have made them more attractive for use in mathematics and science classrooms. Because these tools have been around for a while in computer or graphing-calculator form, we asked ourselves what we have learned about using these devices in the classroom.

CONNECTING GRAPHS WITH PHYSICAL CONCEPTS

One advantage of an MBL is its ability to display graphical representations of data in real time. To what extent does this feature play a role in conceptual understanding? Is the simultaneous display of the graphical representation with the physical event the main feature that makes MBLs effective? Brasell (1987a) suggests that the immediacy of graph production is probably the most important feature of MBL activities. She discovered that a delay of even twenty seconds between the conclusion of the physical event and the graph display makes a difference in the students' ability to link the graph and the physical concept.

Immediacy of graph production is probably the most important feature of MBL activities

Beichner (1989, 1990) suggests that simultaneity is not the only factor affecting the link between a graph and its physical event. He used a video recreation of an event along with the graphical representation so that the student saw the moving object and its graph at the same time. Although Brasell (1987a, 1987b) reported that significant differences in students' ability to link a graph with its physical event were caused almost entirely by simultaneous graph production, Beichner found no significant differences while using reanimation. Beichner concluded that the student's ability to control the environment plays a vital role in his or her understanding of the physical event. Besides the presence of technology, some affective aspect of the experimentation process may drive the student to seek closure on an issue and thus actively pursue an understanding.

Nakhleh and Krajcik (1991, p. 19) observed that "students using MBL activities appeared to construct more powerful and more meaningful chemical concepts." They cited chemistry students' concept maps that showed stronger connections among the concepts of acid, base, and pH. Although Nakhleh and Krajcik cautioned that students need careful task analysis, directed teaching, and class discussion to counteract the formation of inappropriate concepts, they speculated that on-screen graphs allowed MBL students to focus more on *what* was happening in an activity. The MBL maintained the graph as a constant reference while students used their short-term memory to make predictions and construct possible explanations for the graph. This finding is consistent with that of Brasell (1987b). ➔

Applying concepts learned with the MBL also seems to give students a sense of confidence in their work. Mokros (1986) reported that a group of females who had constructed a velocity-time graph for an accelerating cart knew that the slope of the resulting graph had to be positive. However, when a teacher stated that the graph was incorrect and that the line should be horizontal, they argued that their graph was correct and that the slope had to be nonzero for the speed to go up. These students had resolved the issue of slope-height confusion, in which students believe that the fastest rate of change of a graph occurs when the graph is at its highest point (Nemirovsky, Tierney, and Wright 1998; Mokros and Tinker 1987; McDermott, Rosenquist, and van Zee 1987).

Students need to see a variety of graphs to connect them with physical concepts

To connect graphs with physical concepts, students need to see a variety of graphs representing different physical events (McDermott, Rosenquist, and van Zee 1987). For example, when students take readings to study the relationship between time and the temperature of a cooling body, they see a graph of a decreasing exponential function. See **figure 4.** Similarly, the relationship between time and voltage of a decaying capacitor yields another graph of a decreasing exponential function. Observing isomorphic concepts, especially those that are prevalent in nature, may aid in the abstraction of mathematical concepts.

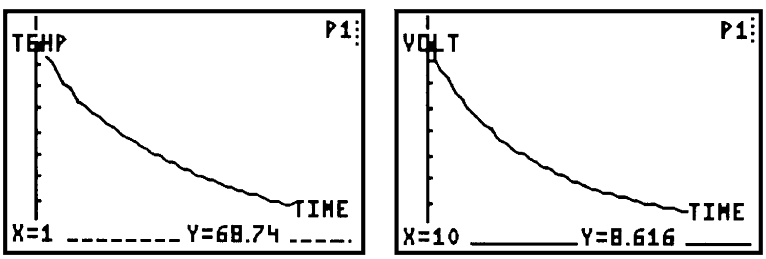

Fig. 4
Exponential model for two different physical events

Using MBLs, Linn (1987) observed the transfer of relationships just described. Students in her study gained considerable understanding of graphing by observing the relationships of heat energy and temperature. They extended their understanding to interpreting motion graphs, although they had not studied kinematics or motion within the graphing environment. For example,

> As a result of studying graphs about heat and temperature, students could correctly interpret a graph showing the speed of a bicycle when the bicycle ascended a hill and then descended the hill. Prior to instruction, many students assumed that when the graph increased, the bicyclist was going up the hill (Linn 1987, p. 8).

Linn's students had resolved graph-shape-and-path-of-motion confusion.

Bassok and Holyoak (1989) found that isomorphic concepts in the mathematics classroom helped students transfer these mathematical concepts from algebra to physics. When linear functions were studied in a general sense in mathematics, students tended to transfer that understanding into the physics context. However, when physics content isomorphic to that in the mathematics curriculum was addressed in the physics classroom, transfer of concepts from physics to mathematics did not occur. For example, when physics students studied Hooke's law, which states that the force on a spring is proportional to the length of its stretch, they observed a linear, that is, a mathematical, relationship; yet they did not typically notice the connection with physics content when they then experienced linear functions in mathematics. Using MBL activities to link concepts from such other disciplines as physics may improve the link with mathematics as well.

CONNECTING GRAPHS WITH THE REAL WORLD

Students may have difficulty distinguishing between the functional relationship of two variables and the visual stimuli received when observing the actual physical event. The most common misconceptions here are graph-as-a-picture confusion, where students do not see a graph as a relationship between variables but rather as one object (Dunham and Osborne 1991; Mokros and Tinker 1987), and graph-shape-and-path-of-motion confusion, mentioned previously. Students often believe that the shape of the graph should resemble the shape of the physical setup of the experiment (McDermott, Rosenquist, and van Zee 1987; Clement 1989; Monk 1990, 1994). If a ball is given an initial velocity on a level "frictionless table," as shown in **figure 5**, the student expects the graph of

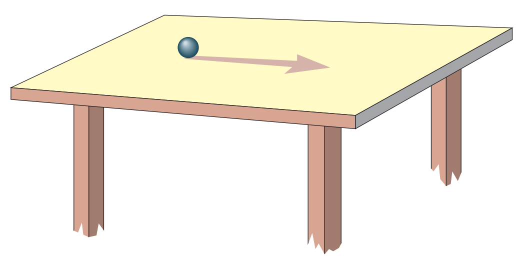

Fig. 5
Ball rolling at constant velocity on tabletop

position versus time to also be horizontal rather than a straight line with nonzero slope, as shown in **figure 6.** Choosing the appropriate graph to explore can be important in counteracting this misconception. For example, if the student used MBL or CBR to examine a velocity-time graph of this same event, the graph would be "flat," as shown in **figure 7,** thereby reinforcing the misconception. Thoughtful use of examples and nonexamples is beneficial.

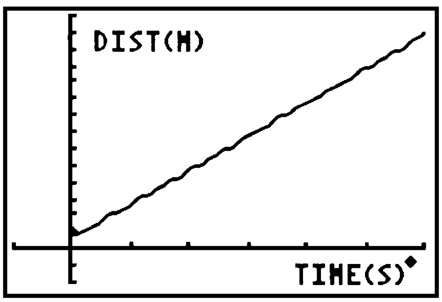

Fig. 6
Distance-versus-time graph of rolling ball on tabletop

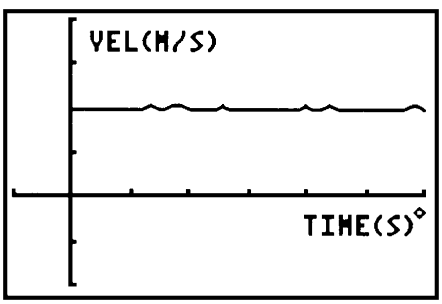

Fig. 7
Velocity-versus-time graph of rolling ball on tabletop

Real-time data collection seems to be the most effective way to connect a graph with the real-world experiences of the student (Brasell 1987b; Nakhleh and Krajcik 1991; Laws 1989). If this theory is correct, then the immediacy of the graph production could help students see real-world relationships rather than simply take visual information and remember a picture of the event. Laws (1989, p. 6) states that

> MBL stations give students immediate feedback by presenting data graphically in a manner that students can learn to interpret almost instantly. This provides a powerful link between real events that can be perceived through the senses and the graph as an abstract representation of the history of these events. Thus, MBL tools provide an ideal medium to support the development of physical intuition through direct inquiry.

Monk and Nemirovsky (1994) meticulously describe one student's experience with a physical event and the graph corresponding to the event. The student's understanding of rate of change evolves as he interacts with the device and graph in a real-time graphing environment. In this instance, the real-time graphing facilitates the deepening of graphical understanding.

TRANSITIONING BETWEEN GRAPHS AND PHYSICAL EVENTS

A vital skill in science is the ability to leap back and forth between a graph and the physical event that the graph describes. The question is, How can we, in practice, help students make the leap from the physical event to the graph and back? Bruner (1966) suggests a progression from enactive to iconic to symbolic representations, that is, the student moves from physically modeling the problem with materials (*enactive*) to diagramming or graphing (*iconic*) to putting the problem into an abstract mathematical form (*symbolic*). A CBR or any form of MBL equipped with a motion probe makes this progression possible.

Brasell (1987b) and Mokros (1986) began with enactive representations using MBL activities to reproduce the motion for a given graph. Mokros used the roles of "dancer" and "choreographer" with students. The choreographer's job was to explain to the dancer what he or she had to do to reproduce the graph given by the teacher. Students had to translate the graphical representation into a series of verbal directions and thereby exhibit an understanding of the various aspects of the graph. In both studies, students were significantly more successful in transferring between a physical event and its graph after using an MBL in real-time mode.

A student needs to be flexible when interpreting graphs

Although linking a physical event with its graph is important, the student also needs to be flexible when interpreting graphs. Consider the motion experiments represented in the graphs in **figure 8**. Here different physical events produced the visually similar position-time, velocity-time, and acceleration-time graphs. Dealing with an apparent conflict between similar graphs arising from different physical events can reinforce the way that information is obtained from each graph. To find velocity, the student must calculate slope at a given point on the first graph, whereas the student simply reads the second graph's value at a given time. Alternatively, the student must approximate area under the curve to find velocity from the third graph. ➔

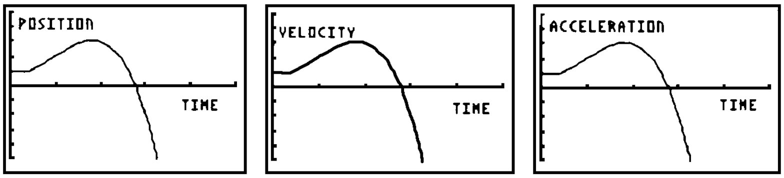

Fig. 8
Different physical events producing the same graphical feedback

Likewise, students should see a variety of graphs of the same event to experience differences in the way that information is presented. For example, students created the distance-time, velocity-time, and acceleration-time graphs in **figure 9** by walking back and forth in front of a CBR. The event in this instance was obviously the same, since the experiment was conducted only once, but the graphs are visually different because of the information displayed. This sort of experience forces students to confront many of the previously mentioned graphical misconceptions.

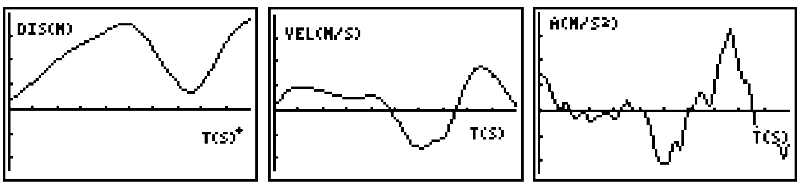

Fig. 9
Same physical event producing different graphical feedback

Students refine their conceptions in a gradual and continuous way

BUILDING GRAPHICAL CONCEPTS THROUGH STUDENT DISCOURSE

Coupling CBL technology with student communication can aid in developing mathematical and scientific concepts. Svec (1995, p. 23) concluded that "activities which emphasize qualitative understanding, requiring written explanations, cooperative learning, eliciting and addressing students' prior knowledge and employing the learning cycle are more effective for engendering conceptual change." Cooper (1995) found that students need to have time to rehearse their developing communication skills as part of their investigation so that they can effectively construct physics concepts.

Hale (1996) examined how students constructed and repaired conceptual understanding using discourse within a CBL environment. One drawback that Hale found for using CBL in cooperative groups was that sometimes, through discourse, groups would converge on a misconception. However, she suggests that using whole-class discussion following an exploration can promote further discourse while repairing any misconceptions. Incomplete understanding is a part of constructing concepts; eliminating it from the learning process is not necessarily desirable. Nakhleh and Krajcik (1991) claim that the high rates of appropriate and inappropriate conceptual links exhibited by students in their study indicate that the students were positively engaged in restructuring their knowledge. Monk and Nemirovsky (1994) suggest that students' misconceptions are not simply replaced by correct conceptions but that students refine their conceptions in a gradual and continuous way. In some studies (Nemirovsky, Tierney, and Wright 1998; Monk and Nemirovsky 1994), this gradual development is accomplished, in part, by student-interviewer discourse.

SUGGESTIONS FOR CLASSROOM USE

Two practices that offer promise in connecting graphs with physical events are prediction and duplication activities. Students benefit from explaining what they think will happen before they conduct an experiment. Students also apparently make connections if they are challenged to reproduce a given motion graph by acting it out and seeing the results in real time. Hale (2000, p. 416) reports a typical student's perspective with Ben's comment, "Doing that one lab where we actually had to come up with the scenarios and then kind of play them out to see whether they worked—that helped out the most I think."

Engaging students in activities that demonstrate the relationship among different types of graphs is also beneficial. Letting students deal with different graphical representations of the same event can help develop understanding of how information is conveyed by various types of graphs.

CONCLUSIONS

What, then, are the reasons for success with MBLs? Mokros and Tinker (1987) give several reasons why MBL technology is useful in connecting graphs and physical events: MBLs use multiple modalities, pair events in real time with their symbolic representations, provide scientific experiences similar to those of scientists in actual practice, and eliminate the drudgery of graph production. Thornton and Sokoloff (1990) warn that the tools themselves are not enough but that gains in learning appear to be produced by a combination of the MBL devices and appropriate curricular material that guides the students to examine appropriate phenomena. They, as well as Mokros and Tinker, suggest that encouraging collaboration is an added benefit of MBLs.

For motion phenomena, using simultaneous graph production to link a graph with a physical concept seems to be essential. However, future research needs to address this issue for such other physical phenomena as temperature. We might expect that simultaneous graph production is not necessary in some settings, because the human senses cannot easily distinguish among varying states for all phenomena. For example, the average person perceives differences in velocity more easily than differences in temperature. Two people walking at, say, 2 MPH and 4 MPH can easily be distinguished; however, the difference in temperature between an object with a temperature of 2°C and another object with a temperature of 4°C is very difficult to distinguish.

Although the literature suggests benefits from using MBL technology, we must also consider problems that may arise if we do not pay attention to how the technology is implemented. Some studies indicate that without proper precautions, technology can become an obstacle to understanding (Lapp 1997; Bohren 1988; Nachmias and Linn 1987). Future research also should address how students view the authority of technology in problem solving.

Research suggests that we can be optimistic about the benefits of MBL and CBL use in forming graphical concepts. However, it is too early to draw final conclusions. Further study is needed before the research community can make any definitive statements on the pedagogical advantages of data-collection devices.

Problems may arise if we do not pay attention to how the technology is implemented

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