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What Are MBLs for? An Example from Introductory Kinematics

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Teaching physics in the laboratory, and more specifically, the use of computers in the physics laboratory is a question of worldwide concern. In this article the authors shall try to validate the use of microcomputer-based laboratories (MBL), based both on theoretical and empirical grounds. Furthermore, an example of an MBL in introductory kinematics is proposed.

In 1998, a brief discussion was held in the Physics Learning Research List, arising from some questions asked by one of the participants, Marcelo Robles Castillo (1998):

> I am new in this List and I want to know if you have discussed previously the use of computers in Lab. I think computers are not as useful there as many people may think. Perhaps if the experience is carefully designed... But students don't understand what is going on; they only see numbers or graphs, usually teachers don't operate correctly the PC and sensors, and at depth, what are now the objectives of the activity of laboratory in Physics? (Anyway, what are the classical objectives of lab in Physics?).

> Yes, I know, I like Lab too. But without an emotional argument, why do we teach at Lab? And why do we use computers? Are there any references somewhere?

Some of the participants in this physics education research list provided their colleague with several important references, both published or online manuscripts, but the most interesting response came from Dr. Pratibha Jolly (1998):

> The “list” of nice experiments that can be set up in the laboratory is fairly large - most of them do yield neat data. (See for instance the work of Thornton & Sokoloff (1990), Priscilla Laws (1997), and many others).
>
> The problem is replicating these in your laboratory. That requires apart from the requisite hardware and software (often multiple copies of expensive setups), a lot of experience. And you are right, of course, the full battery of Murphy’s laws gets activated any time you try even a simple computer based experiment. In India (also Chile?) we don’t have PASCO, VERNIER, et al. supplying the essential hardware/software and so there is the additional challenge of learning enough to build it all up. The question then is: Is it worth the effort? I am convinced it is.

As can be seen from this short discussion, teaching physics in the laboratory, and more specifically, the use of computers in the physics laboratory is a question of worldwide concern. In the following sections the authors try to validate Dr. Jolly’s assertion, based both on theoretical and empirical grounds. Furthermore, an example of an MBL in introductory kinematics is proposed.

THE TRANSMISSION MODEL OF INSTRUCTION

Laws (1997), the coordinator of the Workshop Physics Project at Dickinson College (Pennsylvania), quoted Millikan’s words dating more than 100 years ago:

> I had become thoroughly disillusioned by the ineffectiveness of the large general lecture courses of which I had seen so much in Europe and also in Columbia, and felt that a collegiate course in which laboratory problems and assigned quiz problems carried the thread of the

> course could be made to yield much better training, at least in physics....I started with the idea of making the whole course self-contained....I abolished the general lectures...This general method of teaching...has been followed in all the courses with which I have been in any way connected with. (Millikan, 1950)

Millikan's conclusions about the ineffectiveness of lectures in introductory physics courses have been reconfirmed by Bligh's (1978) more recent research on the impact of lectures in over 200 college-level courses of all types. Bligh concluded that lectures are best for inspiration and for the transmission of information but they are not effective for teaching concepts.

Nevertheless, the prevalent practice found today in physics education results from the so-called transmission model of instruction. In this model, students are exposed to content mainly through lectures and are expected to absorb the transmitted knowledge in ready-to-use form. Although it is not a model of learning per se, the transmission model does make a crucial assumption about learning, namely that the message the student receives is the message the teacher intended (Mestre, 1991).

The transmission model is used largely by default, both because it is the instructional method by which we were taught and because it may be the only instructional method most teachers know. Educational research (Driver, Guesne, & Tiberghien, 1985); Peters, 1982; Mestre & Touger, 1989) shows that the traditional science instructional method is ineffective in altering student misconceptions and simplistic understandings. Even at the university level, students continue to hold fundamental misunderstandings of the world about them: any science learning remains within the classroom context and has no effect on their thinking about the larger physical world, independent of the apparent skill of the teacher (Halloun & Hestenes, 1985a). Thornton (1987) claimed that even successful students who can solve all the problems at the end of a chapter generally lack physical intuition.

THE CONSTRUCTIVIST MODEL OF INSTRUCTION

Unlike the transmission model, the second major instructional practice, which has emerged over the last two decades, begins with what is commonly termed the constructivist model of learning, or simply constructivism. A constructivist model of learning assumes the existence of learners' conceptual schemata and the active application of these in responding to and making sense of new situations. Science education researchers have adopted Kelly's theory of Personal Constructs (as cited in Pope & Keen, 1981) as a viable means of constructivist theory because his approach is based on the metaphor of “a man as a scientist.”

Watts and Bentley (1987) claimed that constructivist theories of learning understand processes of conceptual change in school science as being motivated by dissatisfaction with students’ existing ideas in the face of empirical evidence, images, analogies, or instruction. The change appears to occur where students are encouraged to make their own ideas explicit so that ensuing explorations will find them wanting (Strike and Posner, 1985).

Hewson and Hewson (1984) claimed that, for a conceptual change to take place, instruction should reduce the plausibility of the existing conceptions by illustrating how those conceptions are not satisfactory and then encourage the acceptability of the new conception. The motivation for change arises when the student recognizes that the new conception is more fruitful than the old ones.

Use of teaching strategies, which influence conceptual change, could positively affect student performance. The constructivist approach is based on a view of learners as active and purposive in the learning process and involved in bringing their prior knowledge to construct meanings in new situations (Driver, 1987). Such teaching requires a thorough understanding of subject-matter knowledge, including knowledge of children’s likely preconceptions and of representations of subject matter that students can grasp. Conventional science instruction often fails to address or to change misconceptions about physical phenomena that students bring with them to class. Even good students who do well on course examinations often continue to hold conceptions that are at variance with the scientific theories they have studied. Teachers must know how to identify students’ misconceptions and know how to challenge them (Neale, Smith, & Johnson, 1990). The key aspects of constructivism that should influence the materials for developing students’ understanding, can be expressed as the need for teachers: (a) to have knowledge of students’ existing understanding in the targeted conceptual areas and to use this as a starting point for the design of appropriate teaching materials; (b) to provide experiences that will help students confront discrepancies between their own incorrect or limited views and accepted scientific views; and (c) to verify that students do in fact adhere to correct scientific views.

Such processes place unusually heavy cognitive demands on teachers because of frequent unexpected events, which require immediate decisions. Consequently, general teaching strategies must incorporate both instructional methodology and content, and induce students to make changes in their beliefs of how the world works (Dykstra, Boyle, & Monarch, 1992). Some procedures based on the constructivist view have been shown to be effective (Clement, 1988; Arons, 1990; Thornton & Sokoloff, 1990). Although these strategies require that students experience phenomena, which run counter to their existing beliefs, they rely upon the development of a supportive classroom climate.

These approaches to learning claim that learning is an active and constructive process that depends upon the mental activities of the learner. They also ascribe considerable importance to the role played by prior knowledge in the acquisition of new knowledge. In general, this constructivist view supports teachers who are concerned with the investigation of students' ideas and who develop ways that incorporate these viewpoints within a learning-teaching dialogue.

Redish (1997) has summarized a number of principles that may get students both to hear what we are trying to say and to change their deeply held ideas. These principles have been developed as a result of research in physics education:

1. Go from the concrete to the abstract.
2. Put whatever is new into a known and understood context.
3. Make students articulate what they have seen, done, and understood in their own words.
4. To change people's ideas, you must first get them to understand the situation, then make a prediction, and finally, to see the conflict between their prediction and their observation.
5. Explaining to someone a concept often has little effect in developing his or her thinking or understanding of that concept. Learning includes doing, but "hands-on" activity does not suffice. It must be "brains-on"—that is a cognitive activity that leads to the reconstruction of currently held concepts or the emergence of new ones.
6. "Constructive" activities in which students feel they are in control are much more effective than activities in which the students are being shown results, no matter how eloquently or lucidly the results are presented.

LEARNING PHYSICS IN THE LABORATORY

Access to laboratories and experiences of inquiry have long been recognized as important aspects of school science. Most of the curricula developed in the 1960s and 1970s were designed to make laboratory experiences the core of the science learning process (Shulman & Tamir, 1973). Science in the laboratory was intended to provide experience in the manipulation of instruments and materials, which was also thought to help students in the development of their conceptual understanding.

It is hard to imagine learning to do science, or leaning about science, without doing laboratory or fieldwork. Experimentation underlies all scientific knowledge and understanding. Laboratories are wonderful settings for teaching and learning science. They provide students with opportunities to think about, discuss, and solve real problems.

Despite the importance of experimentation in science, laboratories often fail to convey the excitement of discovery to the majority of our students (Laboratories, 1997). A vivid description of the situation in science laboratories was provided by ethnographic studies of high school science in Australia and the US (Gallagher & Tobin, 1987; Tobin & Gallagher, 1987). These studies discussed several elements as constitutive for the problems with laboratory teaching. Experimental tasks often embody a cookbook approach. Students follow recipes for gathering and recording data without a clear sense for the purposes, procedures, and their interconnections. Typically, students work their way through a list of step-by-step instructions, trying to reproduce expected results and wondering how to get the right answer. These tasks have low cognitive demands and provide a context that precludes reflective thought. Consequently, students engage in activities not intended by the curriculum planners. They spend much of their laboratory time in off-task activity with short periods of attention to get the work completed. As Redish (1994) described: “Many of us who have taught introductory physics for many years recall with dismay a number of salient experiences: a reasonably successful student who can produce a graph but can’t say what it means.”

Although the impact of physics laboratory activities on learning is long debated in literature (DeBoer, 1991; Arons, 1993), they can provide excellent opportunities for students to apply (and examine views of) relevant concepts that might not have been considered before. However, when students are regimented by laboratory manuals that dictate “what to think, how to think, and when to think, lab activities essentially lose impact for learning” (Pushkin, 1997).

Teachers are beginning to realize that their subject matter-content is not the focus. The content provides something to think about, but cognitive instruction provides the ways to engage students in dealing with that content in a thoughtful manner (Fogarty & McTighe, 1993).

Over the last few years, some interesting projects have been developed, following some of Arons’ (1993) guiding instructions for learning in the physics laboratory. He proposed some modes of inquiry and thinking that seem to promise greater effectiveness and firmer justification for maintaining the laboratory as an essential component of physics teaching:

1. Observing phenomena qualitatively and interpreting observations.
2. Forming concepts as a result of observations.
3. Building and testing abstract models in the light of observation and concept formation.
4. Figuring out how a piece of equipment works and how it might be used.
5. Deciding what to do with a piece of equipment, how many measurements to make and how to handle data.
6. Asking or pursuing "How do we know...? Why do we believe...? What is the evidence for...? questions inherently associated with a given experiment.
7. Explicitly discriminating between observation and inference in interpreting the results of experiments and observations.
8. Doing general hypothetico-deductive reasoning in connection with the laboratory situations.

Arons agreed, on one hand, with the view that tightly structured and directed laboratory experiments are dull and demoralizing for the students and generate little in the way of concept development or physical understanding. On the other hand, he thought that the other extreme of completely unstructured situations, in which students are supposed to conduct their own observations, inquiry, and final syntheses, are also ineffective.

This approach is very similar to the constructivist model of teaching. From a constructivist point of view, each learner actively constructs and reconstructs his or her understanding rather than receiving it from a more authoritative source such as a teacher, a textbook, or a laboratory manual. As a consequence, constructivism implies that learners must be given opportunities to experience what they are to learn in a direct way and the time to think and make sense of what they are learning. Laboratory appeal as a way of allowing students to learn with understanding and, at the same time, engage in the process of constructing knowledge by doing science (Tobin, 1990).

STUDENTS' ENGAGEMENT IN PHYSICS LABORATORY ACTIVITIES

Improving laboratory instruction has become a priority in many institutions, driven, in part, by exciting programs being developed at various colleges and high schools. Some laboratories, guided by Arons' (1993) methods, encourage critical and quantitative thinking, some emphasize demonstration of principles or development of lab techniques, and some help students deepen their understanding of fundamental concepts.

Hake (1992) demonstrated the relative success of active engagement methods in what he has called Socratic Dialog Inducing (SDI) laboratories in high school and college. SDI laboratories emphasize experience with simple mechanics experiments and facilitate interactive engagement of students with course material. They are designed to promote students' mental construction of concepts through their (a) conceptual conflict, (b) extensive verbal, written, pictorial, diagrammatic, graphical, and mathematical analysis of concrete Newtonian experiments, (c) repeated exposure to experiments at increasing levels of sophistication, (d) peer discussion, and (e) Socratic dialogue with instructors.

SDI labs have been shown to be relatively effective in guiding students to construct a coherent conceptual understanding of Newtonian mechanics. The method might be characterized as "guided construction," rather than "guided discovery," or "inquiry."

Roth (1994) set up an instructional environment in a laboratory grounded in constructivist epistemology that emphasized both the individual and collaborative construction of knowledge. The high school physics students were encouraged to take individual responsibility for their learning and to participate in the decision making with respect to such issues as assessment, organization of the learning environment, access to resources, and the establishment of research teams. The students were introduced to new units with a range of demonstrations during which they encountered new instruments, apparatus, or software. They were encouraged to research questions that emerged from these demonstrations. The demonstration materials were then made available for the students to familiarize themselves with the equipment and tools. Subsequently, they began an investigation, in groups of three or four, by formulating a focus question and planning the data collection—for the first experiment in a unit, the teacher often suggested a research question. The students then set up the apparatus, collected the data, and submitted the data to a computer-based mathematical and graphical analysis. Each group discussed its results, consulting other groups and the teacher, and then prepared a report.

Roth (1994) found a remarkable ability and willingness to generate research questions (of all the research questions investigated, the students framed about two-thirds on their own). Students were also willing and able to design and develop apparatus for data collection, to deal with problems arising during implementation of the experiment, and to pursue meaningful learning during the interpretation of data and graphs to arrive at reasonable answers of their focus questions.

Laws (1997) is the coordinator of a project called Workshop Physics running successfully for ten years at Dickinson College. In these years the Physics project team members developed computer tools, apparatus, and curricular materials to facilitate activity-based learning in the laboratory, without lectures.

Workshop Physics consists of a series of related activities that help students to achieve several educational goals:

1. To develop a conceptual understanding of physics phenomena and to be able to relate that understanding to a mathematical representation of phenomena.
2. To achieve wider scientific literacy (cf. Arons, 1990).
3. To develop skills in the use of contemporary apparatus and computer tools for the collection and analysis of scientific data.
4. To be motivated to learn more science both formally and informally.

Activities include discussions with instructors and classmates, qualitative observations, data gathering, guided-equation derivations, problem solving, as well as the use of spreadsheets, computer-based laboratory tools, and video analysis tools for the collection and analysis of data as well as for both analytical and numerical modeling using spreadsheets.

The common attribute of these successful physics laboratories activities is that they are learner-centered. They induce students to become active participants in a scientific process in which they explore the physical world, analyze the data, draw conclusions, and generalize their newly gained scientific understanding to phenomena that are a part of their everyday world. Those who have invested in innovative laboratory programs report very encouraging results: better understanding of the material and much more positive attitudes toward the laboratory (Laboratories, 1997).

MICROCOMPUTER-BASED LABORATORIES

Thornton (1987) claimed that to make laboratories engaging and effective for developing useful scientific intuition, students need powerful, easy to use, scientific tools with which to collect physical data and to display them in a manner that can be manipulated, thought about, and remembered. To allow students to concentrate on the scientific ideas that are the goal of their investigations, such tools should eliminate the drudgery associated with data collection and display, and should be structured to encourage an inquiry approach to science. Sabelli (1995) claims:

> We teach as we were taught. But what and how we learn have always depended on the tools available to students and teachers and should change with significant changes in the tools available. As the affordability of powerful microcomputers increases, educators become responsible for exploring the profound pedagogical implications of the changes brought about by technology on the practice of science.

Technology can help make science more understandable and attractive to the increasingly large numbers of students and future citizens.

Increased computer power allows learners to make concrete representations of abstract concepts to explore scientific phenomena with computational models as an adjunct to experimentation and theory. Universal access to computing methodology can substantially increase the number of students who learn science by doing science, and not just hearing about science.

Modern computer technology might help constructivist applications, in which the computer is used to enable the students' personal explorations by giving them tools (and guidance) to work things through by themselves. The computer, in what is called Microcomputer-based Laboratories (MBL) can capture and display data from the real world quickly and accurately. This helps students make the link between concrete elements in the real world and the abstract representations of physics. This has been demonstrated to be much more effective in producing good learning of concepts than traditional methods (Redish, 1997). Researchers claim that MBL activities are effective in improving students' understanding of graphs of physical events (Mokros, 1986; Thornton, 1987). This has been supported by research done on high school and university students (Thornton & Sokoloff, 1990; Solomon, Bevan, Frost, Reynolds, Summers, & Zimmerman, 1991; Trumper, 1997). In typical MBL applications, the computer is interfaced with probes to measure physical phenomena such as motion, light, temperature, force, pressure, or sound. The student is provided with a software tool that makes the measurement function easily accessible, "giving the computer the same role in the laboratory as electronic instrumentation, except that it is extremely flexible" (Mokros & Tinker, 1987). Using the same software with different sensors allows students to have a consistent, friendly interface for gathering data so that they can focus their attention on the underlying physics principles. After using these tools within a guided-discovery curriculum in mechanics, up to 90% of introductory students answer simple conceptual questions in the Newtonian way, whereas in traditional instruction the average is close to 20% (Sipson & Thornton, 1995).

Graphs are the central means of communication with students in the developing of the MBL materials. Data are reported to the students in the form of graphs that evolve as the experiment progresses. McKenzie and Padilla (1984) stated that graphs are an important tool for enabling students to predict relationships between variables and substantiate the nature of these relationships. They have even shown that inadequate mastery of graphing skills is a major stumbling block to understanding scientific concepts (Shaw, Padilla, & McKenzie, 1983). According to Gardner (1983), "Mastering of symbolic systems...might even be regarded as the principal mission of modern educational systems." Real time graphing of data on the computer screen is fast and dynamic with the graph forming on the screen as the event progresses; thus both the speed and the dynamism may have a considerable impact on information processing. Researchers (Mokros, 1986; Mokros & Tinker, 1987; Thornton, 1987) suggested that this linking in time of a physical event with a simultaneous graphic representation may facilitate an equivalent linking in memory. Real time graphing allows learners to process information about the event and the graph simultaneously rather than sequentially. Short-term, or working memory is limited in capacity, in retention time, and it is limited in the rate at which it can transfer information to long-term memory. Brasell (1987) assumed that the initial entry and processing of information in the brain takes place in short-term memory, and he claimed that "real-time graphing may allow rapid cognitive linking within short-term memory...and thus increase the likelihood of the linked information being transferred to long-term memory as a single unit."

Thornton and Sokoloff (1990) conjectured that the MBL activities they had designed were unusually effective for five reasons:

1. Students focus on the physical world.
2. Immediate feedback is available.
3. Collaboration is encouraged.
4. Powerful tools reduce unnecessary drudgery.
5. Students understand the specific and familiar before moving to the more general and abstract.

These conjectures are consistent with modern theories of learning (see references in Redish, 1994), including those built on the work of Piaget and Vygotsky. To this list Redish, Saul, & Steinberg, 1997 added a sixth conjecture:

6. Students are actively engaged in exploring and constructing their own understanding.

These conjectures appear to be confirmed by the different studies previously quoted and by Thornton and Sokoloff's (1990) testimony while visiting an MBL laboratory:

> A visit to an MBL laboratory illustrates the contrast with a traditional class. Students are actively involved in their learning. They are sketching predictions and discussing them in groups of two or three. They are appealing to features of the graphs they have just plotted to argue their points of view with their peers. They are asking questions and, in many cases, either answering them themselves or finding the answers with the help of fellow students. There is a level of student involvement, success, and understanding that is rare in a physics laboratory.

Laboratory teaching methods may vary widely, but the authors believe there is no substitute for an instructor circulating among the students, answering and asking questions, pointing out subtle details or possible applications, and generally guiding students' learning. Some instructors rely on a lab handout, not to give cookbook instructions, but to pose a carefully constructed sequence of questions to help students design experiments that illustrate important concepts. The main advantage of the well-designed handout is that the designer more closely controls what students do in the laboratory.

In conclusion, changing the way that students learn involves rethinking the way we teach in the laboratory, writing new laboratory handouts, setting up a training program for teaching assistants, and perhaps designing some new experiments for a wide range of students from elementary school to university level.

A MICROCOMPUTER-BASED LABORATORY IN INTRODUCTORY KINEMATICS

Students bring to the formal study of physics an intuitive sense of the meaning of common concepts associated with motion. Ideas of location, distance, time, duration, speed and acceleration exist as somewhat vague and undifferentiated notions. Although inadequate for a description of motion in the physicist's sense, terms like speed and acceleration have a commonly shared meaning in everyday life.

In addition to having difficulties with the concepts of distance, velocity, and acceleration (Halloun & Hestenes, 1985b; McDermott, Rosenquist, & van Zee, 1987), students appear to have problems with graphing. The most frequent graphing misconceptions held by high-school students seem to be confusion between the slope and height of lines on the graph, and the tendency to see the graph as a picture rather than as a symbolic representation of information (Clement, Mokros, & Schultz, 1986; Mokros & Tinker, 1987).

In kinematics, it is difficult to separate the slope/height confusion in interpreting graphs from the confusion between distance and velocity which appears to be prevalent among students from high school to college (McDermott et al., 1987).

Teachers often tacitly assume that a good performance on course examinations, which mainly include problem-solving, indicates that this type of understanding has been achieved. However, Redish et al. (1997) claimed that many students who can do well on conventional test questions cannot correctly apply physical concepts to real situations. McDermott et al. (1987) found that students who have no trouble plotting points and computing slopes, frequently "cannot apply what they have learned about graphs from their study of mathematics to physics." The analysis of graphing errors identified in their study indicated that problems students have with graphing cannot be attributed to inadequate preparation in mathematics. Many of them are "a direct consequence of an inability to make connections between a graphical representation and the subject matter it represents."

There are many factors which probably contribute to these difficulties, including a lack of understanding of kinematic concepts, confusion between the concepts and a tendency to draw a curve that looks like a picture of the motion of the object. However, even if students are adept at sketching or interpreting graphs for unidirectional motion, they may still have considerable difficulty when dealing with motion involving a reversal of direction. In this case "a graph of velocity versus time includes both positive and negative values of velocity, and it is the negative values that seem to cause additional confusion for the students" (Goldberg & Anderson, 1989).

The authors propose a simple MBL laboratory in introductory kinematics, a "guided constructed" activity in which students can deal with distance, velocity, and acceleration graphs, and the relation between them. Moreover, they can investigate the relation between these graphs and their actual own movement, which has no analytical description.

For the motion studies an ultrasonic motion detector of the type available from *Vernier*[1] *Software, Pasco*[2], *V-Scope*[3], *Logal*[4] or other sources was used. These motion sensors send out short pulses of high-frequency sound and measure the time for the pulses to bounce off the target and return. Using that information and the speed of sound it calculates the distance between the target and the sensor. Velocities and accelerations can be found from numeric differentiation. Any of these quantities may be graphed on the screen as data are taken, and any one or more are available for display immediately after the measurements are completed.

The sensor was put on a table, which was defined as the origin of the movement; the ceiling of the room is the bouncing target. During the measurement, the student holds the motion detector in his or her hand, moving it to and from the ceiling in a slow and continuous way, even below its initial position on the table. The student must maintain the emitting part of the sensor parallel to the ceiling during all the measurement (about 9 seconds). It was noted that after several failures, all the students obtain a successful outcome of their hand movement.

It is important to note that the movement of the hand parallel to the ceiling does not affect the measurement of the distance between the sensor and the ceiling (the Doppler effect does not spoil the precision of the measurement because of the slow motion of the hand).

The student can see on the screen, in real-time, the graphical representation of the displacement of the sensor relative to the table, and its velocity obtained by numerical differentiation (Figures 1 and 2), as a function of time. The measurement results are stored in an electronic spreadsheet for later printing.

At the beginning of the inquiry the displacement versus time graph only was presented on the screen, and the students were asked to answer several questions such as:

1. At which time did you begin to move your hand?
2. What are the time intervals in which the velocity has a positive sign?
3. What are the time intervals in which the velocity has a negative sign?
4. At which time (or times) does the instantaneous velocity become equal to zero?
5. What are the time intervals in which the velocity increases?
6. What are the time intervals in which the velocity decreases?
7. How do the answers to the preceding questions relate to the actual movement of your hand during the measurement?

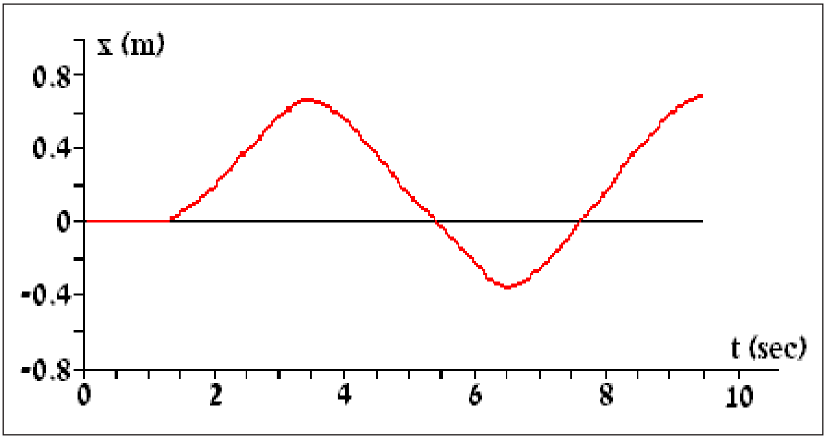

Figure 1. Displacement versus time graph of the motion

At a second stage, we present the velocity versus time graph together with the displacement versus time graph in order to:

1. Check the students' answers to the preceding questions.
2 Get a general understanding of the relation between the two graphs.
3. Learn about the relation between the velocity versus time graph and the actual movement of the hand (for example, what is the meaning of a positive and negative sign velocity).
4. Ask students to investigate by themselves the velocity versus time graph in order to predict how the acceleration versus time graph will look like.

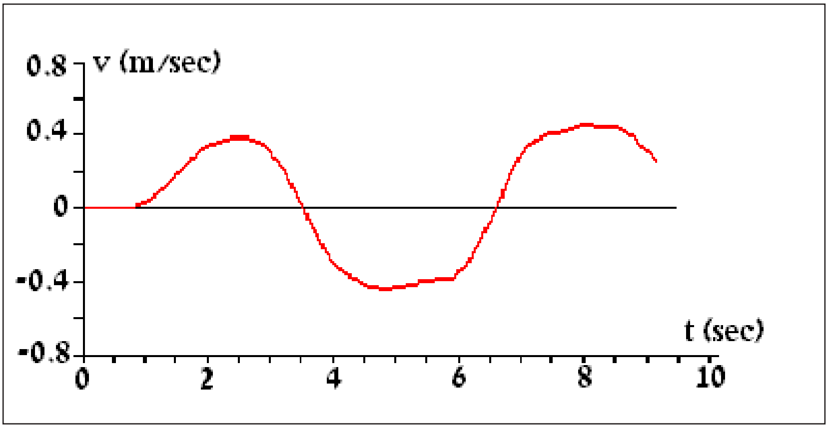

Figure 2. Velocity versus time graph of the motion

At a third stage the acceleration versus time graph is presented (Figure 3) together with the velocity versus time graph to:

1. Check their prediction.
2. Get a general understanding of the relation between the two graphs.
3. Learn about the relation between the acceleration versus time graph and the actual movement of the hand (for example, what is the meaning of the instantaneous acceleration becoming equal to zero).

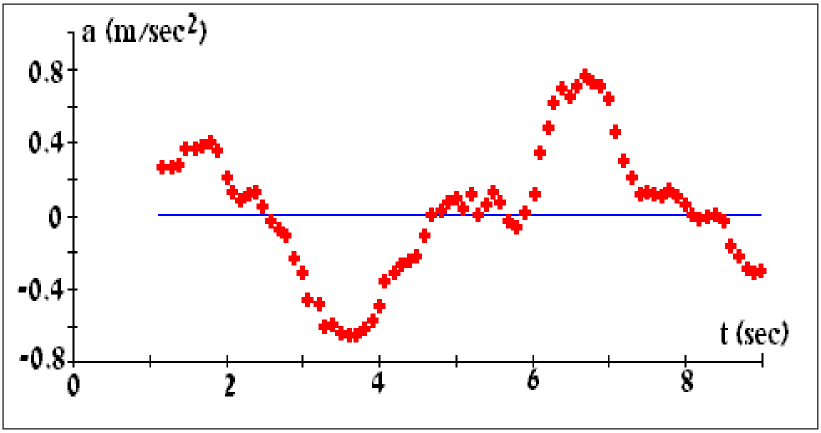

Figure 3. Acceleration versus time graph of the motion

Finally, for some more advanced students, we could try and find some relations between the acceleration versus time and the displacement versus time graphs.

For example:

1. How can we find in the displacement versus time graph the instantaneous zero acceleration times:
   A zero acceleration time occurs when the velocity versus time graph reaches a maximum or a minimum, that is when the velocity versus time graph stops its increase (or decrease) and begins decreasing (or increasing). That is, in the case of a maximum, when the slope of the displacement versus time graph passes from a growing tendency to a decreasing tendency (Figure 4), or in other words, when there is a “saddle point” in the displacement versus time graph.

2. How can we find in the displacement versus time graph the time intervals in which the velocity increases and the time intervals in which it decreases: The velocity increases between a minimum and a maximum of the velocity versus time graph, and it decreases between a maximum and a minimum. As we have seen earlier, the maxima and minima of the velocity versus time graph match the saddle points of the displacement versus time graph. For example, when the saddle point shows a transition from a decreasing to an increasing slope in the displacement graph we get a minimum.

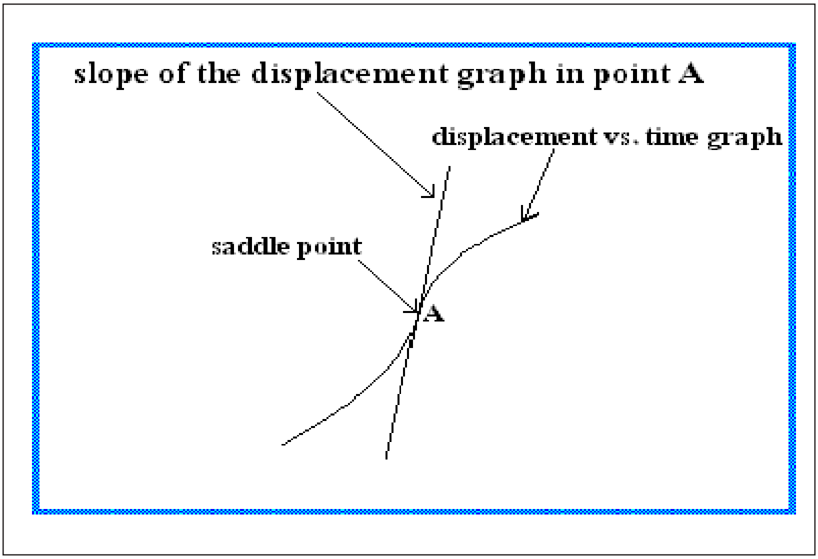

Figure 4. The saddle point in the displacement versus time graph

From these two examples the importance of finding not only the maxima and minima in the displacement versus time graph, but also the saddle points, is seen. Even through this simple activity, one of the most exciting features of the motion detector is its ability to detect and display graphs of the motion of any object can be seen. Thus, instead of using complex apparatus like nearly frictionless air tracks, which are not common to students' everyday experiences, the motion probe may be used to measure the motion of the student's own hand. There is no other way of accurately displaying such graphs, certainly not in real time.

Specifically, the proposed exercises may clarify:

1. How the displacement and velocity versus time graphs relate to the actual movement of the hand.
2. What is the relation between the displacement and velocity versus time graphs.
3. What is the relation between the velocity and acceleration versus time graphs.
4. The sign convention for velocities.

Mokros and Tinker (1987) suggest four possible reasons for the effectiveness of the MBL activities, as they have been reported in the preceding section: "MBL uses multiple modalities; it pairs, in real time, events with their symbolic representations; it provides genuine scientific experiences; and it eliminates the drudgery of graph production."

In the MBL activities students manipulate physical laboratory materials and mainly use their own physical movements as data. The physical experience is reinforced by the visual experience of seeing the physical phenomena change.

The learning provides a real time link between a concrete experience and the symbolic representation of that experience. According to Piaget's theory this may be a bridge between concrete and formal operations. The graph that emerges while a student is moving may be seen as an immediate abstraction, and Brasell (1987) has shown that immediacy here is crucial since even short delays in presenting the graph might impair learning.

The MBL activities give students the opportunity to experience the excitement of the process of science—"the creative building and testing of models to explain the world around them" (Thornton & Sokoloff, 1990). These gains in learning physics concepts appear to be produced by the combination of the computer tools and the appropriate guiding materials.

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