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ABSTRACT

This document reports a project, entitled Workshop Physics, that involved the development and testing of introductory physics materials to enable instructors to abandon the traditional separation of lecture and laboratory in favor of a workshop format. The Workshop Physics courses emphasize cognitive development enhanced by direct experience and the use of microcomputers as tools for observations, data collection, and data analysis. Written materials developed for the project included workbook style activity guides that serve as textbook supplements for both calculus-based and non-calculus-based course sequences. In addition, microcomputer-based laboratory materials were developed. These included a series of electronic sensors; an RS-232 compatible microcomputer interface; and software packages for data collection on the Macintosh computer. Evaluation results have shown gains in student attitude and motivation as well as in specific conceptual areas, computer skills, and experimental techniques emphasized by the course. The appendices, which make up the greater part of the report, contain samples of curricular materials, a syllabus for each of the 28 activity guide units, and reprints of published articles that were developed from the project. (PR)

COVER SHEET

Grantee Organization: Department of Physics and Astronomy
Dickinson College
Carlisle, PA 17013

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Project Dates: Starting Date: October 1, 1986
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Number of months: 36

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Grant Award:

Year 1	$68,629
Year 2	75,190
Year 3	85,301
Total	$229,120

Summary

This project involved the development and testing of introductory physics materials to enable instructors to abandon the traditional separation of lecture and laboratory in favor of a workshop format. The Workshop Physics courses emphasize cognitive development enhanced by direct experience and the use of microcomputers as a tool for observations, data collection, and data analysis. Written materials developed for the project included workbook style Activity Guides that serve as text book supplements for both calculus-based and non-calculus-based course sequences. In addition, microcomputer-based laboratory (MBL) materials were developed. These included a series of electronic sensors; an RS-232 compatible microcomputer interface (ULI); and software packages for data collection on the Macintosh computer. As a result of enhanced funding during year three, the Tools for Scientific Thinking Project centered at Tufts University joined the project. Year three activities included: (1) co-development at Dickinson College and Tufts University of several more MBL software and hardware packages for the Macintosh computer; (2) preparation of the MBL materials, Workshop Physics Activity Guides, and the Tools for Scientific Thinking Curriculum Guide for commercial distribution; and (3) conduct of a more thorough evaluation of the pedagogical advantages of using MBL materials in the "workshop" environment.

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The following project products are available from Vernier Software Co., 2920 S.W. 89th Street, Portland, OR 97225 (503) 297-5317:

The Workshop Physics Activity Guides (Calculus-Based and Non-Calculus-Based)
The Workshop Physics Calculus-Based Apparatus Guide
The Tools for Scientific Thinking Curricular Guide
Universal Lab Interface and Software Developer's Guide
Radiation Detector/Force Probe
Dickinson Software for the Macintosh Computer: Event Timer /Event Counter
Tufts MBL Software for the Macintosh Computer: MacMotion /MacTemp

The following publications have resulted from the project:

Laws, Priscilla W., Workshop Physics: Replacing Lectures with Real Experience, The Conference on Computers in Physics Instruction: Proceedings. (Addison Wesley: Reading, MA, 1990).

Thornton, Ronald K., Tools for Scientific Thinking: Learning Physical Concepts with Real-Time Laboratory Measurement Tools, The Conference on Computers in Physics Instruction: Proceedings. (Addison Wesley: Reading, MA, 1990).

Thornton, Ronald K. and Sokoloff, David, Learning Motion Concepts Using Real-Time Microcomputer-Based Laboratory Tools. Publication pending in the American Journal of Physics.

Additional articles are under preparation for submission to the American Journal of Physics during the spring of 1990.

Executive Summary

Project Title: Workshop Physics

Grantee Organization: Department of Physics and Astronomy
Dickinson College
Carlisle, PA 17013

Project Contact: Priscilla W. Laws at (717) 245-1242

A. Project Overview

This project began with a year of planning and baseline testing of students taking introductory physics courses at Dickinson College using traditional teaching formats. The project involved development and testing of introductory physics materials to enable instructors to abandon the traditional separation of lecture and laboratory in favor of a workshop format. Over 200 students at Dickinson College and a number of students at other colleges and universities gained direct experience with physical phenomena without the aid of lectures either by means of direct observations or observations enhanced by the use of the microcomputer as a laboratory instrument.

Project outcomes include: (1) demonstration of improvements in conceptual learning and student attitudes toward physics over that achieved in traditional introductory physics courses; (2) preparation of written and computer-based curricular materials for commercial distribution to colleagues at other colleges and universities; (3) establishment of a regular sequence of teacher workshops at the semi-annual national meetings of the American Association of Physics Teachers on how to conduct laboratories using MBL instrumentation and how to teach Workshop Physics; (4) provision of information and support to over 150 colleagues at other institutions who are interested in modifying their introductory teaching; (5) publication of three articles on the project as well as the acquisition of material for several more articles now under preparation; (6) delivery by P. Laws and R. Thornton of over 100 talks and workshops at professional meetings and physics colloquia; (7) receipt of two national awards for curricular innovation; and (8) receipt of four additional grants from FIPSE and NSF to continue with the development and dissemination of the program to other institutions.

B. Purpose

The four major objectives of Workshop Physics are to: (1) help students develop a positive attitude toward science, (2) enhance scientific literacy, (3) reduce misconceptions, and (4) retain traditional text book problem solving skills. Although we have learned how to achieve dramatic conceptual gains in certain specific areas using kinesthetic experiences and MBL tools, we have also learned that some student "misconceptions" are very resistant to change. We have come to a new appreciation of the role of teacher-directed discussions and other activities that help students reflect on their experiences. One of the major tasks in the coming three years is to identify the types of concepts requiring follow-up work with students and to develop teaching strategies and materials to provide maximum learning gains.

C. Background and Origins

The project grew out of a dissatisfaction with the effectiveness of lectures in helping students acquire fundamental concepts in introductory physics courses and a growing recognition that the Microcomputer-Based Laboratory (MBL) instrumentation being developed for physics experiments at Dickinson College had great potential in helping students grasp fundamental physics concepts on an intuitive level.

This project benefited by a tremendous amount of institutional support for the purchase of 20 Macintosh computers and the remodeling of two substandard introductory physics laboratories into "ideal" settings for computer-enhanced classroom/laboratory learning. Five of the full-time teaching faculty in the Department of Physics and Astronomy have helped with the planning and teaching of the courses.

The project has enjoyed additional outside support both from FIPSE and NSF to extend the development of course materials for use at other institutions and for the conduct of teacher workshops during the summer of 1990. Both the Merck Foundation and Educom in conjunction with the National Center for Research to Improve Postsecondary Teaching have provided national recognition for the Workshop Physics program by honoring it with awards for curriculum innovation. As part of its award program the Merck Foundation has donated $15,000 to the science program at Dickinson College.

D. Project Description

Although the two programs share a common approach and educational philosophy, the Tools for Scientific Thinking Project has focused on the development and extensive testing of a set of seven guided inquiry units in the college and university laboratory setting. These units have been designed to be used independently of knowledge gained in lectures so that they can be easily added to the laboratory component of more traditional university courses. On the other hand, the Workshop Physics Project is centered around the development of a new learning environment in which formal lectures have been abandoned to create a maximum amount of time for active learning. The Workshop Physics staff has generated and classroom tested a set of 28 guided inquiry units. Several of the units developed in the Tools for Scientific Thinking Project have been adapted for use in the Workshop Physics units. The topics span many of those normally covered in introductory physics courses. Students experience physical phenomena directly whenever possible. Macintosh SE computers are used extensively by students to collect, display, and analyze data as well as for solving numerical problems, modeling, and graphic simulations.

E. Project Results

Evaluation

A range of instruments have been used to evaluate both the Workshop Physics and Tools for Scientific Thinking programs. We have discovered demonstrable gains in student attitude and motivation as well as in specific conceptual areas, computer skills, and experimental techniques emphasized by the course. In addition, there has been no noticeable loss in the more conventional problem solving skills needed for success in typical intermediate level physics courses. Physics is still hard to master and there is no magic wand available to wave over the students, but we are helping students to begin to achieve some mastery over more skills required "to do physics." Since we have additional funding, refinement and extension of the course materials and evaluation of their impact on students will continue for the next few years.

Dissemination

Interest in using the materials is high. More than 130 people have asked to be on a mailing list to receive information about course materials. At least twenty additional colleges and universities have used parts of the curriculum even before its official dissemination. Project staff have offered six oversubscribed workshops at the national meetings of the AAPT, and eight international workshops have been offered. The project directors, Ron Thornton and Priscilla Laws, have given invited talks throughout the United States and in six foreign countries. Some upcoming speaking engagements include a pair of invited talks at the January 1990 AAPT meeting in Atlanta (Thornton & Laws), two additional contributed talks (Penny & Laws and Laws, et. al), a talk at the annual meeting of the Association of American Colleges in San Francisco (Laws), an invited talk at the Macademia Conference in Daytona Beach (Laws), and physics colloquia at Michigan State University (Laws) and Rutgers University (Laws). A number of related projects have been funded in the last three years. These include funds from: Dickinson College (for equipment and remodeling), FIPSE (for adaptation of curricular materials for university settings and a teacher workshop), NSF (for laboratory instrumentation and a teacher workshop), the Massachusetts Department of Education (for teacher training), and Apple Computer (for equipment).

F. Summary and Conclusions

Introductory physics courses in the United States are in need of reform. The classroom testing of the curricular materials already developed for the Tools for Scientific Thinking and Workshop Physics projects indicate that they provide effective means of addressing the problems encountered in typical university level introductory physics courses. Evaluation data in the Tools for Scientific Thinking project show substantial and persistent mastery of basic physical concepts, not often learned in lectures. Preliminary assessments of the Workshop Physics project at Dickinson College show dramatic increases in the motivation of students while they are taking introductory physics courses. The detailed evaluation of the learning gains of students should add to the body of physics education literature, and thus contribute to better models for teaching introductory physics. The curricular materials produced should allow college and university instructors to experiment with more interactive approaches to the teaching of introductory physics. There is strong evidence of interest in adopting materials from both projects among college and university physics teachers. Other funding agencies at the state and federal level are contributing in important ways to the acquisition of equipment for new development efforts and to dissemination of curricular materials. The work of both projects is already gaining a national and international reputation.

G. Appendices

The written materials appended to the full report include sample curricular material, reprints of three articles (either published or pending) based on work undertaken in the projects funded by this grant, a list of individuals, organizations, colleges and universities who have inquired about the Workshop Physics Program, and a draft flyer describing commercial availability of materials developed. Supplemental materials include: (1) Video tape excerpts of award ceremonies in which the Workshop Physics Project was honored by the Merck Foundation and NCRIPTAL; (2) Copies of the MBL software developed by the Project; and (3) Diskette copies containing the Activity Guides developed for the Workshop Physics Project.

The Report Narrative

A. Project Overview

This project began with a year of planning and baseline testing of students taking introductory physics courses at Dickinson College using traditional teaching formats. The project involved development and testing of introductory physics materials to enable instructors to abandon the traditional separation of lecture and laboratory in favor of a workshop format. Over 200 students at Dickinson College and a number of students at other colleges and universities gained direct experience with physical phenomena without the aid of lectures either by means of direct observations or observations enhanced by the use of the microcomputer as a laboratory instrument.

Project outcomes include: (1) demonstration of improvements in conceptual learning and student attitudes toward physics over that achieved in traditional introductory physics courses; (2) preparation of written and computer-based curricular materials for commercial distribution to colleagues at other colleges and universities; (3) establishment of a regular sequence of teacher workshops at the semi-annual national meetings of the American Association of Physics Teachers on how to conduct laboratories using MBL instrumentation and how to teach Workshop Physics; (4) provision of information and support to over 150 colleagues at other institutions who are interested in modifying their introductory teaching; (5) publication of three articles on the project as well as the acquisition of material for several more articles now under preparation; (6) delivery by P. Laws and R. Thornton of over 100 talks and workshops at professional meetings and physics colloquia; (7) receipt of two national awards for curricular innovation; and (8) receipt of four additional grants from FIPSE and NSF to continue with the development and dissemination of the program to other institutions.

B. Purpose

Workshop Physics and Tools for Scientific Thinking share a common educational philosophy. Both projects assume that the acquisition of scientific literacy as defined by Arnold Arons[1] is more important than engagement with the traditional textbook problem solving that currently dominates introductory physics.

Table 1: Some Elements of Scientific Literacy
(from Arons, "Achieving Wider Scientific Literacy", *Dædalus*, Spring 1983)

1. Recognition that scientific concepts (e.g. velocity, force, energy, etc.) are human creations and not real objects accidently discovered.

2. Recognition that scientific concepts require careful operational definition. That is to realize that a concept involves idea first and name afterward and that understanding does not reside in the technical term.

3. Comprehension of the distinction between observation and inference.

4. Ability to distinguish between the occasional role of accidental discovery and the deliberate strategy of forming and testing hypotheses.

5. Understanding the meaning of the word "theory" and having experience with how theories are formed, tested, and accepted provisionally.

6. Comprehension of the limitations inherent in scientific inquiry and the kinds of questions that can and cannot be asked and answered.

7. Development of enough knowledge in an area of science to allow intelligent study and observation to lead to subsequent learning without formal instruction.

The four major objectives of Workshop Physics are to: (1) develop a positive attitude toward science, (2) enhance scientific literacy, (3) reduce misconceptions, and (4) retain traditional text book problem solving skills. Although we have learned how to achieve dramatic conceptual gains in certain specific areas using kinesthetic experiences and MBL tools, we have also learned

[1]A. Arons, "Achieving Wider Scientific Literacy", *Dædalus*, Spring 1983

that some student "misconceptions" are very resistant to change. We have come to a new appreciation of the role of teacher-directed discussions and other activities that help students reflect on their experiences. One of the major tasks in the coming three years is to identify the types of concepts requiring follow-up work with students and to develop teaching strategies and materials to provide maximum learning gains.

In administering the project, we initially underestimated the need for full-time administrative help. In addition, the development, testing and pre-commercial dissemination of the computer interface, sensors, and software have taken far more time than we expected. This part of the enterprise which is deemed crucial pedagogically is badly underfunded, and our focus on making the development of the computer-based materials happen by hook or crook has meant that we are not as far along in the assessment of the project outcomes as we had hoped to be by September 30, 1989.

C. Background and Origins

The project grew out of a dissatisfaction with the effectiveness of lectures in helping students acquire fundamental concepts in introductory physics courses and a growing recognition that the Microcomputer-Based Laboratory (MBL) instrumentation being developed for physics experiments at Dickinson College had great potential in helping students grasp fundamental physics concepts on an intuitive level.

This project benefited by a tremendous amount of institutional support. Upon receipt of the FIPSE grant in 1986, Dickinson College allocated $50,000 for the purchase of 20 Macintosh computers and another $66,000 to remodel two substandard introductory physics laboratories into "ideal" settings for computer-enhanced classroom/laboratory learning. Five of the full-time teaching faculty in the Department of Physics and Astronomy have helped with the planning of the courses, taught sections, and written curricular materials for the courses. Two

individuals have spent their sabbaticals at Dickinson to help with the program and bring changes back to their own institutions.

We had some initial difficulty in trying to accommodate three weekly two-hour sessions for each workshop physics section into the course schedule scheme. This ruffled feathers in the Chemistry Department where schedule conflicts were anticipated for their majors. At times students complained that we were working them too hard. However, a small liberal arts college setting has been an ideal place to try new ideas because in addition to the special support afforded us by the College, the small class sizes, level of support from academic computing, the comraderie among departmental colleagues, and the closeness between faculty and students have allowed us to iron out kinks and rough spots in the curricular materials with a minimum of agony.

Additional outside support came from an NSF ILI grant for $29,000 which was matched by the College to purchase additional computers, video equipment, and software for the project. A FIPSE dissemination grant of $7,900 was awarded to give a one-week seminar on Workshop Physics to teachers at other colleges and universities in the summer of 1900. An NSF Faculty Enhancement Grant of $62,300 was awarded for the conduct of a two-week seminar on Workshop Physics in June 1990. Effective October 1, 1989 FIPSE awarded Dickinson College and Tufts University another three-year grant to adapt and refine materials developed in the Workshop Physics and Tools for Scientific Thinking Projects for use at larger universities where several hundred students are enrolled in introductory physics courses. Both the Merck Foundation and Educom in conjunction with the National Center for Research to Improve Postsecondary Teaching have provided national recognition for the Workshop Physics program by honoring it with awards for curriculum innovation. As part of its award program the Merck Foundation has donated $15,000 to the science program at Dickinson College. In addition, the Educational Research Division of Apple Computer has awarded two equipment grants totaling more than $100,000 to the Center for the Teaching of Science and Mathematics at Tufts University in

the past year and a half for continued research on student learning and development of new MBL curricular materials.

D. Project Description

Influenced in part by the successes of the FIPSE funded Professional Development Program at U.C. Berkeley directed by Uri Teisman and Robert Fullilove, both the Workshop Physics and Tools for Scientific Thinking projects share an emphasis on the processes of verbal communication and peer learning. Students in both projects are given ample opportunity to plan activities and discuss findings with each other in and out of the classroom environment. Both projects make extensive use of microcomputers, not as tutorial devices or teaching machines, but rather for the acquisition of both qualitative and quantitative information about physical phenomena.

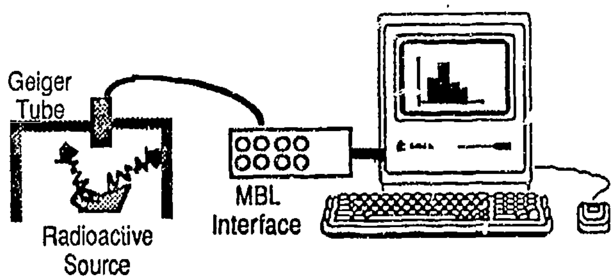
Although the two programs share a common approach and educational philosophy, they have some fundamental differences that complement each other. The Tools for Scientific Thinking Project has focused on the development and extensive testing of a set of seven guided inquiry units in the college and university laboratory setting. These units have been designed to be used independently of knowledge gained in lectures so that they can be easily added to the laboratory component of more traditional university courses. On the other hand, the Workshop Physics Project is centered around the development of a new learning environment in which formal lectures have been abandoned to create a maximum amount of time for active learning. The Workshop Physics staff has generated and classroom tested a set of 28 guided inquiry units. Several of the units developed in the Tools for Scientific Thinking Project have been adapted for use in the Workshop Physics units. The topics span many of those normally covered in introductory physics courses. Project resources have not allowed for detailed measurement of learning gains in Workshop Physics on a unit by unit basis. However, the insights about the learning process gained from the detailed assessments conducted in the Tools for Scientific Thinking Project have served to

inform the development of new curricular materials in the Workshop Physics Project.

1. Tools for Scientific Thinking, Tufts University (Oct 1986-Sept 1989)

This project, described in more detail in Appendices E and F uses the microcomputer equipped with sensors, a special interface, and software to collect and display real scientific data instantaneously in graphic form. Such a setup is commonly known as a Microcomputer Based Laboratory or MBL. The graphs on the computer screen might represent the change of a measured quantity such as the distance of a student from a motion detector, the counting of a beta particle for a radioactive nucleus, or the temperature of a cooling object as time passes. An MBL setup is illustrated in Figure 1 below.

Fig 1: An MBL setup to display beta particle counts from a radioactive source.



Using Microcomputer-based laboratory (MBL) sensors and software, students can simultaneously measure and graph such physical quantities as position, velocity, acceleration, force, temperature, light intensity, sound pressure, nuclear radiation, current and voltage.

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 those events. Thus, MBL tools provide an ideal medium to support the development of physical intuition through direct inquiry – an approach strongly recommended by cognitive scientists and physics educators.

Inquiry-based curricular materials and MBL tools have been developed for seven topics covered in traditional introductory physics courses:

1. motion (kinematics)
2. force and motion (dynamics)
3. heat and temperature
4. simple harmonic oscillations (including energy)
5. sound
6. visible light
7. electricity

The MBL unit on motion has been reproduced in Appendix B.

Seven colleges and universities have been involved in the primary testing of the materials including: California State Polytechnic University, Dickinson College, Massachusetts Institute of Technology, Muskingham College, the University of Oregon, Tufts University, and Xavier University.

2. The Workshop Physics Program, Dickinson College (Oct 1986-Sept 1989)

The lack of integration of laboratory and classroom instruction inherent in the use of the Tools for Scientific Thinking materials in the laboratory has not been a problem for the Workshop Physics program where the normal distinction between lecture and laboratory has been abandoned. Students and the instructor meet for three two-hour sessions each week in which they can move freely between guided activities and discussions. (See Appendix D for a more complete description of the Workshop Physics Program). In Workshop Physics, curricular materials have been created for a range of activities that cover most of the traditional introductory physics topics. These topics are listed in Appendices A and C. Among other things students pitch baseballs, whack bowling balls with twirling batons, attempt pirouettes, construct digital circuits, ignite paper by compressing gas, design engine cycles with rubber bands, and use an MBL system to monitor radon on campus. Students experience physical phenomena directly whenever possible. Macintosh SE computers are used extensively by students to collect, display, and analyze data as well as for solving numerical

problems, modeling, and graphic simulations. This allows students to perform and analyze many more qualitative observations and quantitative experiments than is typically possible in an introductory physics laboratory.

The design of learning activities in each unit are adapted from a learning sequence suggested by David Kolb and others. The sequence begins with student predictions of the outcome of casual, qualitative observations of a phenomenon of interest. Students proceed to actual observations and reflect on the results of these observations. With the help of the instructor, the outcome of the observations is often the basis for the development of a formal mathematical description of a phenomenon. The sequence culminates in providing the students with an opportunity to apply their new understandings to the solution of a novel experimental or theoretical problem or to perform a quantitative experiment that verifies the predictions of the formal theory. The content of the courses was cut by about 30% to allow for the longer time needed for students to begin mastering important physics concepts. Preliminary assessments of learning gains in covering the subset of MBL units adapted from the Tools for Thinking Project indicate that content should be cut even more, if maximum educational benefits are to be realized.

During the 1986-87 academic year, five members of the Department of Physics and Astronomy drafted Student Activity Guides for both the calculus and non-calculus sections of the course. Development of hardware and software for MBL photogate timing and nuclear counting was started, and new apparatus was designed to aid students in direct observations. The Workshop courses were introduced to about 70 students at Dickinson College during the fall of 1987. The courses are now undergoing a third full year of classroom testing, and the Activity Guides are being revised for the third time by Profs. P. Laws, J. Luetzelschwab, and R. Boyle. These Activity Guides will be distributed by Vernier Software beginning in January 1990.

E. Project Results

Evaluation

A range of instruments have been used to evaluate both the Workshop Physics and Tools for Scientific Thinking programs. In the Tools program pre- and post-tests were administered after each laboratory unit involving the use of MBL materials. In some cases the persistence of the learning was tested several months after the original intervention. These tests focused on major concepts and misconceptions identified by researchers. Data show dramatic and persistent learning of physical concepts, not easily learned in lectures, by students who use the MBL curricular materials. (See reprints of articles in Appendices E and F for details). For example, university students who were given two kinematics labs each lasting between 2 and 3 hours were able to reduce error rates on questions aimed at interpreting velocity graphs from a pre-test average of 65% to a post-test average of about 12% as shown in Figure 2 below.

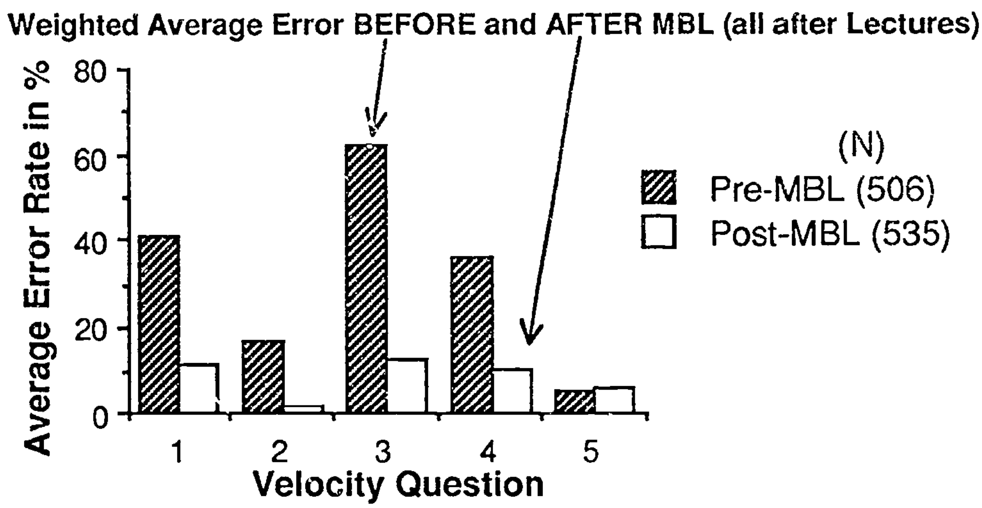


Figure 2

On the other hand, *students from Tufts University and the University of Oregon receiving lectures on the same topic only reduced their average error rates to 50% and thus, had much smaller learning gains.* Additional research with high school populations indicates similar pre- and post-test patterns that appear to be independent of ethnic origin, intended major, or sex. One student at

Tufts after using the MBL motion detector and figuring out the meaning of linear acceleration for herself exclaimed, "Look at me, I'm a scientific humanist!"

Evaluations in the Workshop Physics program started in the Fall of 1986 when pre-workshop physics baseline tests were administered using the Mechanics Concepts test developed at Arizona State University, select portions of the AP Physics examination, the standard Dickinson College course evaluation form, and a special questionnaire asking students to rate how various course activities contributed to their learning, to estimate how much time they spent on the course, and to describe what changes they would most like to see made. Each of these tests has been administered one or more times to students who have taken Workshop Physics along with post tests for MBL activities developed in the Tools for Scientific Thinking project. In addition, the enrollment of Workshop Physics graduates in advanced courses was monitored and performance in subsequent courses and on MCAT examinations was assessed. Results are summarized briefly in this narrative. More details will be reported in an article now being prepared for the American Journal of Physics.

The most dramatic impact of Workshop Physics on students is an improvement in their attitude toward the study of physics. In comparison with the time spent on other courses and time spent by cohorts at other institutions, the average student reported working harder on Workshop Physics courses. In spite of this fact, the written comments on the course evaluation forms indicated that the vast majority of the students in the calculus-based course and more than half the students in the non-calculus based course preferred the workshop method to the lecture method. On a nine point quality-of-course scale one calculus section in the spring of 1988 gave the course an average rating of 7.6 and a median rating of 8.0 in spite of the fact that this was the first trial of the second semester calculus-based course. *This was the second highest combined rating given to any of the 117 laboratory science course sections taught at Dickinson in the past three years and thus placed it in the top 2% of the lab science courses offered.* One freshman who enrolled in physics to fulfill the science requirement commented–

> "The intellectual challenge and quality of this course were excellent. Some days after doing an experiment that worked out really well, I would feel as if I accomplished so much. Even after struggling over an experiment for the whole period, finally getting it was a great feeling. I received a lot more from the course than an understanding of physics. The "hands-on" experience was great. . . Besides the physics I learned, just the experience with the computers and equipment have helped me a lot. I have stayed away from computers and been afraid to play around with equipment before, but now I'm not and I can just "dig in". . . .Workshop Physics is Phun!

Although it is too early to be sure of the trends, enrollments in the non-calculus course have remained stable while enrollments in the calculus course are about 15% higher than they were before the program began and enrollment in the sophomore level modern physics course is up by about 50% this year over the pre-program figures. In the past 25 years only one student has gone into high school teaching. Now in its third year, the Workshop program has yielded three physics students who have expressed a desire to become certified in high school teaching. We'd like to think this is a result of Workshop Physics classes being more fun to be in than lectures and conventional laboratories.

The Workshop Physics courses have adopted MBL materials for motion, force, oscillations, and heat and temperature and in some cases adapted them for use with the learning sequences in the Workshop Physics Activity Guides. Learning gains based on pre- and post-tests evaluated as part of the Tools for Scientific Thinking Program are dramatic and entirely consistent with those achieved at other institutions where the MBL materials have been tested. See Appendix F for more details on the outcomes of the general study in which Dickinson's Workshop Physics students participated.

Although the results of pre- and post-testing for the Mechanics Concepts test developed at Arizona State University are difficult to interpret for reasons which will be discussed in the upcoming article, it appears that there are modest overall gains in mechanics concepts as measured by the test over those experienced by Dickinson students before the Workshop Physics program was introduced and over those experienced by students taking lecture based physics courses at other

institutions. There were more demonstrable gains on some key misconceptions for which specific learning sequences were developed. For instance students who whacked bowling balls were superior several weeks later in describing the motion of an object undergoing a constant force perpendicular to the direction of its initial velocity on the Mechanics Concepts post-test.

Performance on problem sets and the problem portion of examinations suggests that students in Workshop Physics have about the same facility with conventional textbook problem solving as their pre-workshop physics cohorts. Ditto for their performance in advanced courses. It is not noticeably better or worse by conventional standards. We know by watching the students as they set up new experiments and handle the computers that they are more literate in the process of scientific investigation. However, we have not developed good measures for evaluating these gains scientifically.

In some ways we were hoping for more dramatic gains across the board for students taking physics using the workshop approach. We have discovered demonstrable gains in student attitude and motivation as well as in specific conceptual areas, computer skills, and experimental techniques emphasized by the course. In addition, there has been no noticeable loss in the more conventional problem-solving skills needed for success in typical intermediate level physics courses. Physics is still hard to master and there is no magic wand available to wave over the students, but we are helping students to begin to achieve some mastery over more skills required "to do physics." Since we have additional funding, refinement and extension of the course materials and evaluation of their impact on students will continue for the next few years.

Dissemination

Although the Workshop Physics materials will not be officially ready for dissemination until January 1990, interest in using the materials seems high. Some of the materials have already been used informally at a number of institutions including the University of Oregon, the University of Nebraska,

Johnson C. Smith College, Bellevue Community College, Troy State University, Ohio State University, and several high schools. More than 130 people have asked to be on a mailing list to receive information about course materials.

The Tools for Scientific Thinking materials have been widely disseminated and adopted. In the Fall of 1989 Ohio State University acquired motion detectors, software, and ULIs for use with 800 students in their introductory physics laboratory. At least twenty additional colleges and universities have used parts of the curriculum even before its official dissemination. Project staff have offered six oversubscribed workshops at the national meetings of the AAPT, and eight international workshops have been offered. Project co-director, Ron Thornton, has given many invited talks in the United States and in six foreign countries. A number of related projects have been funded in the past three years. These include an NSF grant held by Tufts University, Hampton University and the University of Georgia for the training of high school teachers, a two-year-long summer seminar for exemplary high school teachers funded by the U.S. Department of Education, and grants from the states of Massachusetts, Oregon, and Ohio to help with the training of high school science teachers.

About 120 individuals attended one or more of a series of hour-long mini-workshops on computer use in Workshop Physics at the Conference on Computers in Physics Instruction held in August 1988. An invited talk on Workshop Physics was given at that meeting by Priscilla Laws, the project director. Almost 60 people signed up for 20 spaces in a day long combined workshop sponsored by the American Association of Physics Teachers (AAPT) on the Tools for Thinking and Workshop Physics projects held in January 1989 in San Francisco. Two heavily oversubscribed one-day long workshops were given at the June 1989 meeting of the AAPT in San Luis Obispo and are slated to be repeated at the January 1990 meeting in Atlanta. Profs. Laws and Thornton have been giving an average of three major talks each month for the past two years on the Workshop Physics and Tools for Scientific Thinking Projects. Highlights from this fall include talks at Hamilton College (Thornton), Arizona State University (Laws), the Introductory University Physics Project Conference in Denver (Laws), San Francisco State University during the earthquake

(Thornton), and tandem talks at a NATO Advanced Study Workshop in Pavia, Italy (Laws and Thornton) which Prof. Thornton helped to organize.

Some upcoming speaking engagements include a pair of invited talks at the January 1990 AAPT meeting in Atlanta (Thornton & Laws), two additional contributed talks (Penny & Laws and Laws, et. al), a talk at the annual meeting of the Association of American Colleges in San Francisco (Laws), an invited talk at the Macademia Conference in Daytona Beach (Laws), and physics colloquia at Michigan State University (Laws) and Rutgers University (Laws).

Prof. Mary A.H. Brown from Troy State University in Dothan, Alabama spent her 1987-88 sabbatical leave at Dickinson College to help set up the first round of workshop courses. She is now using the materials at her institution. Prof. Desmond Penny of Southern Utah State University has arranged to spend his sabbatical at Dickinson College during the 1989-90 academic year. He will work with the Workshop Physics Program with the idea of setting up a similar program at his university. Prof. Geoffrey Wilson of Johnson C. Smith College is testing our materials with eight black students at Johnson C. Smith University. Profs. Wilson and Penny will be reporting on their experiences in talks at the January 1990 meeting of the American Association of Physics Teachers. Under the aegis of the new FIPSE grant for the Interactive Physics project, colleagues from the University of Oregon, the University of Nebraska, and Boise State University will begin refining and testing materials at their institutions. Introductory physics course organizers at Auburn University, the Air Force Academy, and Arizona State University have also expressed interest in implementing workshop physics programs at their institutions.

Profs. Thornton and Laws are serving as advisors on a pilot project known as CUPLE. This project is centered at the University of Maryland and funded by the Annenberg CPB project and IBM. MBL and curricular materials developed in the Workshop Physics and Tools for Scientific Thinking projects will be used in the development of a sample computer-based unit in mechanics to show the

potential of high technology computer work stations coupled with video input to serve as a learning resource for introductory physics students.

F. Summary and Conclusions

Introductory physics courses in the United States are in need of reform. The classroom testing of the curricular materials already developed for the Tools for Scientific Thinking and Workshop Physics projects indicate that they provide effective means of addressing the problems encountered in typical university level introductory physics courses. Evaluation data in the Tools for Scientific Thinking project show substantial and persistent mastery of basic physical concepts, not often learned in lectures. Preliminary assessments of the Workshop Physics project at Dickinson College show dramatic increases in the motivation of students while they are taking introductory physics courses. The detailed evaluation of the learning gains of students should add to the body of physics education literature, and thus contribute to better models for teaching introductory physics. Furthermore, the actual curricular materials produced should allow college and university instructors to experiment with more interactive approaches to the teaching of introductory physics. The development and implementation of the Workshop Physics courses at Dickinson College have required a tremendous amount of work and planning and probably would not have been successful without the extensive grant aid and staff support it afforded. We are very excited to discover that after three years of effort the ongoing teaching of the Workshop courses is not requiring more effort than our traditional lecture and laboratory courses required. Hopefully by using the materials developed in the program most small to medium-sized liberal arts colleges committed to implementing a Workshop Physics course sequence can do so with affordable support for computer equipment and start-up staff time. After the first two years we would expect that the courses should not require more faculty and staff time to maintain than the traditional courses did.

There is strong evidence of interest in adopting materials from both projects among college and university physics teachers. Other funding agencies at the state and federal level are contributing in important ways to the acquisition of equipment for new development efforts and to dissemination of curricular materials. The work of both projects is already gaining a national and international reputation. The Tools for Scientific Thinking and Workshop Physics projects have proven track records and when combined are in a unique position to continue the development of learning materials that can have an important impact on science education at the university level. Several years of effort have resulted in the development of relationships with physics educators at a host of other colleges and universities. These relationships will facilitate the testing, pedagogical research, and the evaluation necessary for the development of effective curricular materials for introductory physics courses in a wider range of university teaching environments. Most importantly, an experienced, highly qualified, and enthusiastic staff are available to continue the important work of these two projects.

G. Appendices

See attachments on grey paper.

SUMMARY OF APPENDICES
AND SUPPLEMENTAL MATERIAL

for

The Workshop Physics Program
Final Report, December 1989

A.	Reduced sample of curricular materials developed by the Workshop Physics Program.

B.	Reduced sample of curricular materials developed by the Tools for Scientific Thinking Project.

C	The Workshop Physics Syllabus for the 1989-90 Version of the calculus-based introductory physics course sequence indicating the topic for each of the 28 Activity Guide Units.

D.	Paper by Priscilla W. Laws entitled "Workshop Physics: Replacing Lectures with Real Experience," published in the Proceedings of the Conference on Computers in Physics Instruction (Addison Wesley, Reading MA, 1990)

E.	Paper by Ronald K. Thornton entitled "Tools for Scientific Thinking: Learning Physical Concepts with Real-Time Laboratory Measurement Tools," published in the Proceedings of the Conference on Computers in Physics Instruction (Addison Wesley, Reading MA, 1990)

F.	Paper by Ronald K. Thornton and David Sokoloff entitled "Learning Motion Concepts Using Real-Time Microcomputer-Based Laboratory Tools," accepted for publication in the American Journal of Physics.

G.	Dissemination of Workshop Physics and Tools for Scientific Thinking Concepts.

H.	Draft of a flyer describing items developed through the auspices of the Workshop Physics Program and Tools for Scientific Thinking Program that are being distributed by Vernier Software, Inc., Portland, Oregon.

SUPPLEMENTAL MATERIAL

1. Video Tape excerpts of EDUCOM/NCRIPTAL and MERCK awards received for Workshop Physics Program plus scenes of students using hardware and software generated jointly by the Tools for Scientific Thinking project at Tufts University and the Workshop Physics program at Dickinson College

2. Software developed as follows:

Diskette Label	*Contents*
Macintosh MBL Software (Disk 1) Workshop Physics Program	Event Timer V3.0 (for PG Timing) Event Counter V4.0 (MacNuke)
Macintosh MBL Software (Disk 2) Tools for Scientific Thinking	Macmotion V1.9h MacTemp V0.5

3. Diskettes containing Workshop Physics Curriculum
   - Calculus Version (5-Disk Set)
   - Non-Calculus Version (2-Disk Set)

APPENDIX A: Workshop Physics Sample Syllabus and Activity Guide Unit

The Workshop Physics Activity Guide

Instead of spending three hours each week in lectures and three hours in laboratory, Workshop Physics Students attend three two-hour long sessions each week in a laboratory/classroom environment. Students make observations, work problems, do experiments, analyze data, and discuss their findings with classmates, a teaching assistant, and the instructor. Their results are summarized in a written Activity Guide which is handed in for review on a weekly basis.

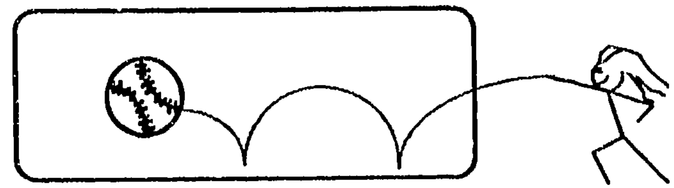
The material on the following pages is a copy of the fourth week-long Activity Guide Unit developed for the calculus-based version of Workshop Physics. This unit is indicated in boldface on the contents list below.

Activity Guide Units

Activity Guide Appendicies:

Name ____________ Section______ Date ________

UNIT 4: TWO-DIMENSIONAL MOTION



The essential fact is that all the pictures which science now draws of nature . . . are mathematical pictures.

Sir James Jeans

OBJECTIVES

1. To review the definitions of *average* and *instantaneous* velocity and acceleration and be able to determine average quantities experimentally using measurements of length and time.

2. To learn to use direct measurements and photogate timing measurements to calculate velocity and acceleration more accurately.

3. To explore the similarity between the type of acceleration that results from falling motion and that which results from tapping a rolling ball continuously.

4. To learn how to use vector mathematics to describe velocities and accelerations in two dimensions.

5. To understand the experimental and theoretical basis for describing projectile motion as the superposition of two independent motions: (1) that of a freely falling body in the vertical direction, and (2) that of a constant velocity in the horizontal direction.

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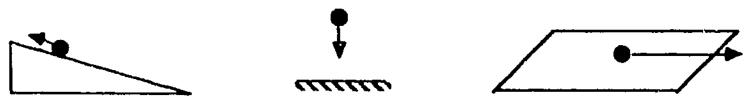
OVERVIEW

The eventual focus of this unit is on the description of motion that occurs when an object is allowed to move freely in both the vertical and horizontal direction close to the surface of the earth. This type of motion is commonly called projectile motion. To understand this motion, it is helpful to study two types of motion separately and then see how they might be combined. The first type of motion involves "falling" along a straight line, such as that which occurs when an object rolls up or down a ramp or is thrown or released straight up or down. This motion can be contrasted with the motion that results when an object rolls or slides horizontally along a level surface. These two motions result in very different types of acceleration.



(a) "Falling" motion along the straight line that lies along the surface of a ramp.

(b) "Falling" motion along a straight vertical or up/down line.

(c) Horizontal linear motion along a level surface

Figure 4-1: Several Types of One-Dimensional Motion; i.e., motion along a straight line

During the first session you will observe and sketch graphs of the motion of a steel ball up and down a 5 meter long inclined track. You can then review similar observations you made using the motion detector for the motion of a cart or rotating cylinder on a ramp. You will use a computer simulation of this same motion to generate a set of idealized graphs for position, velocity, and acceleration vs. time. The simulation will allow you to set up different ramp angles for different parts of the track. Thus, you can study graphical representations of both falling and horizontal linear motion and a host of other "nutty" situations.

Simulations are too idealized for a real examination of motion. The next step is to obtain more precise data on motion using the high precision photogate timers. Thus, the second session will begin with a review of the mathematical definition of average velocity as well as a more careful examination of the mathematical

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definition of both average and instantaneous acceleration. These definitions will be used to calculate the velocity of an object rolling down a ramp.

You will have studied falling motions in one dimension until you are sick of them. Next, by noting the nature of their accelerations, we can ask if there's any way to recreate the same type of accelerated one-dimensional motion by tapping a large rolling ball repeatedly with a rubber mallet.

If a "falling" acceleration can be recreated in one dimension, we can assume that simple two-dimensional projectile motion can be recreated by rolling a ball in one direction and tapping on it at right angles to the direction in which it is rolling. Session three will be devoted to the creation and analysis of two-dimensional motion by tapping a ball with a rubber mallet.

Toward the end of session three you can begin a short lab project in which you use what you know about projectile motion and measuring motion to help you become a master detective and solve a murder mystery.

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SESSION ONE: ONE-DIMENSIONAL MOTION ALONG A RAMP

Observing Motion Along a Ramp

Let's begin our study of one-dimensional falling motions with some direct observations. Suppose we roll a steel ball toward the top of a 5 meter long ramp and then let nature take its course. This scenario is shown in the diagram below.

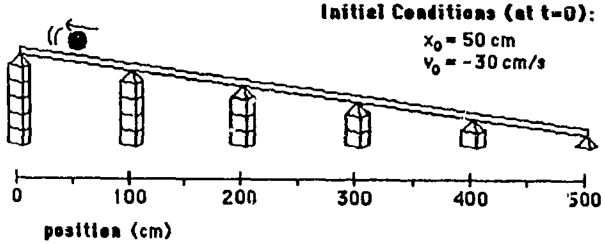
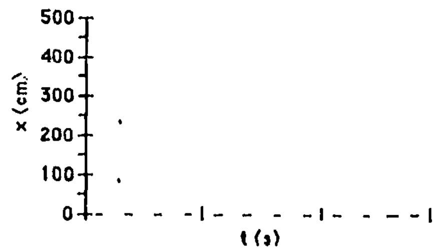


Figure 4-2: A ball rolling up and then down a ramp.

✍GE 4-1: Predicting the Shape of the Position Graph

(a) Imagine the motion. Using the graph framework below and some discussion with your table mates, predict the shape of the graph of position vs. time for the motion described by sketching it. Don't worry about the time scale– that depends on the slope of the ramp.



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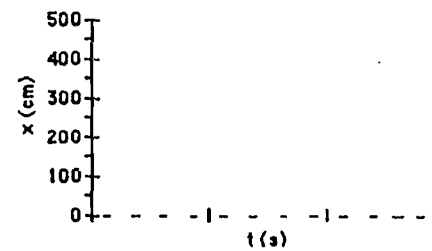
(b) By observing, but not measuring, how the position of the ball varies with time, revise your sketch by using the graph framework below. Be sure to use a solid line for your sketch. Fill in and estimate the time scale by recording some key times on an approximate basis; e.g., the approximate time it takes the ball to travel from–

1. 50 cm to 0 cm
2. 50 cm to 0 cm and back to 50 cm
3. 50 cm to 0 cm, back to 50 cm and then to 500 cm.



— Current Observation
.... Earlier Motion Detector Observation

(c) Look back at the position vs. time graph that you recorded using the motion detector with the cart (or cylinder) traveling up and then down on another shorter ramp. See the position vs. time graph in Unit 3: Investigation 4 on Acceleration, Activity 3 on pages 4-5 and 4-6. Put in a time scale on the horizontal axis. Sketch the observed motion with a dotted line on the graph above; i.e. - - - - - - -. Are the shapes similar or different? Explain.

Describing Changes in Velocity and Acceleration

Let's think about how the *velocity* is changing as the ball travels up and down the ramp. In order to do this let's define the velocity as positive when the ball moves from left to right down the ramp and as negative when the ball moves from right to left up the ramp.

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GE 4-2: Describing Changes in Velocity on the Ramp

(a) Describe as best you can in words how the velocity changes over time. When is it negative, when is it zero, and when is it positive?

(b) Drawing on your experience with the creation of motion detector graphs, define acceleration carefully in words. What is acceleration? For our choice of coordinates when is the acceleration negative? When is it positive?

(c) Now think about the ball starting up and then rolling down the ramp. At what points in time is the acceleration negative, positive, zero? Does it remain constant?

(d) In general, is the acceleration of a moving body that is changing its direction zero at the instant that its velocity is zero? Why or why not?

(e) Describe the acceleration of a penny that has been tossed into the air when it is on the way up, when it is at its peak and when it is on the way down. Does the acceleration change?

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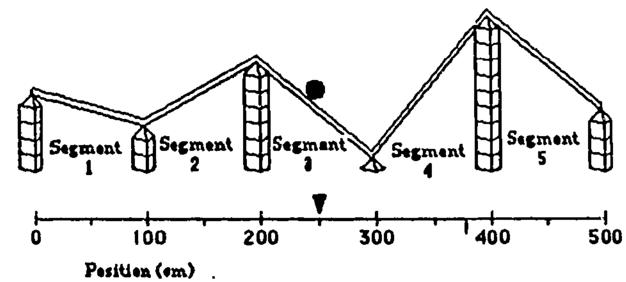
Use of a Graph and Track Simulation on the Computer
You can use special software written for the computer to set up a simulation of your actual ramp and ball situation. The program, called Graphs and Tracks was written by David Trowbridge at Carnegie Mellon University. The program has exercises that allow you to "construct" a series of 5 connected ramp segments with different slopes in an attempt to obtain motion graphs that match those presented on the computer screen. In this way you can use trial and error to test your understanding of what motion graphs from various combinations of ramps will look like.



You can check your sketches of graphs against the graphs produced by the computer based on calculations it has done using theoretical kinematic equations.

To run the Graph and Track software do the following:

1. Load a system and a Graphs and Tracks Disk into the Computer.
2. Open the file called Graphs and Tracks I
3. When you see the title screen, follow the screen instructions.

There are 8 exercises on your disk. You should start by practicing with exercise#1, since it represents a situation which is similar to the real ramp and ball set up you have been using for observations.

GE 4-4: Graphs and Tracks Exercises

You should complete any 3 of exercises 2-8 in the Graphs and Tracks I software and sketch the results on the next page. If you like, for an extra challenge, you can ask your partner to design exercises for you to solve instead of the ones provided. Ask the instructor for details.

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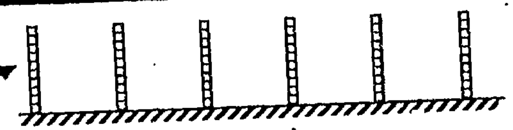
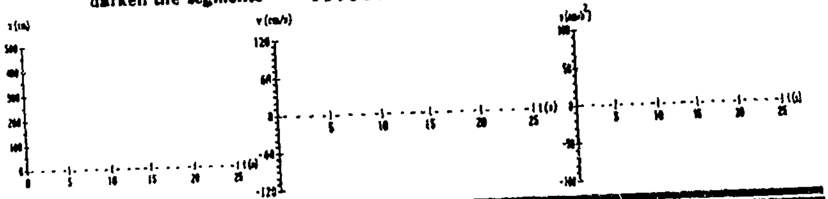
Graphs and Tracks
Exercise # ___

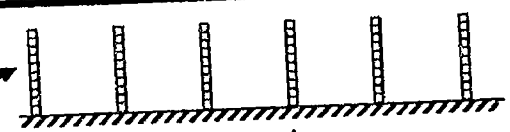
To sketch the ramp darken the segments

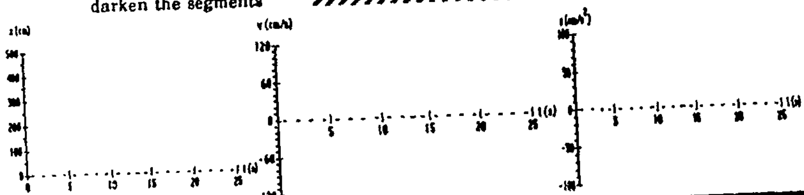




Graphs and Tracks
Exercise # ___

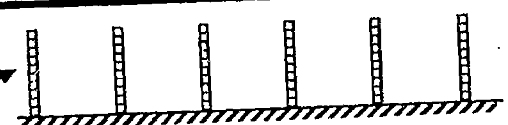
To sketch the ramp darken the segments

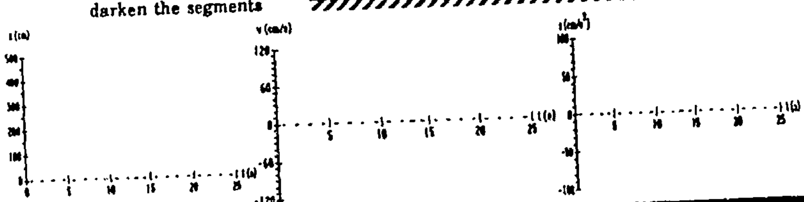




Graphs and Tracks
Exercise # ___

To sketch the ramp darken the segments





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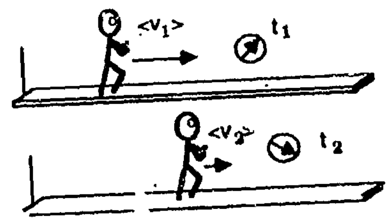
SESSION TWO: MEASURING ACCELERATION DIRECTLY

How Do You Define Acceleration Mathematically?

By considering the work you did with the motion detector, you should be in a position to define average acceleration along a line mathematically in analogy to the mathematical definition of velocity. You may want to review your GE3-1 entry in the last unit.

✍ GE 4-5: Defining Acceleration Mathematically

(a) Let's denote the average velocity by the letter <v> and average acceleration with the letter <a>. Suppose your average velocity is $<v_1>$ at a time t_1 and that the average velocity changes to $<v_2>$ at a later time t_2. Write an expression for the average acceleration in the space below.



Note: Let t_1 and t_2 represent the average times at which the average velocities were measured.

(b) Suppose you are walking away from a motion detector as shown above. How is the rate of your walking changing if $<v_1>$ is greater than $<v_2>$? Is your acceleration positive or negative? Explain.

(c) Suppose you are walking toward a motion detector. How is the rate of your walking changing if $<v_1>$ is greater than $<v_2>$? Is your acceleration positive or negative? *Be very careful with your mathematics on this one. It's tricky!*

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Calculating Accelerations from Measurements
To test your understanding of the meaning of the mathematical definition of acceleration and to be able to calculate accelerations on the basis of measurements you can make in the laboratory, let's consider the following situation. Suppose an ideal cart with no friction in the wheels is rolling down a ramp. One of your classmates measures the position of the cart with the meter stick at three different times. The results are shown in the table below.

t (sec)	x (cm)
0.00	0.00
1.00	0.82
2.00	3.32

✍ GE 4-6: Calculating Acceleration from Direct Measurement
(a) Use the fundamental definition of average velocity to calculate the average velocities from the position measurements in the time intervals 0 to 1 sec and from 1 to 2 sec. Show your calculations clearly in the space below.

(b) Use the values you just calculated for the average velocities and the fundamental definition of average acceleration to determine the average acceleration in the time interval between 0.5 sec and 1.5 sec. Show your calculations clearly in the space below.

Let's consider that the same acceleration was measured with a photogate timer in order to obtain more precise data. Suppose that a lucite strip with stripes of black tape was on top of the rolling cart and that the photogate rig was set up as shown in the diagram on the next page.

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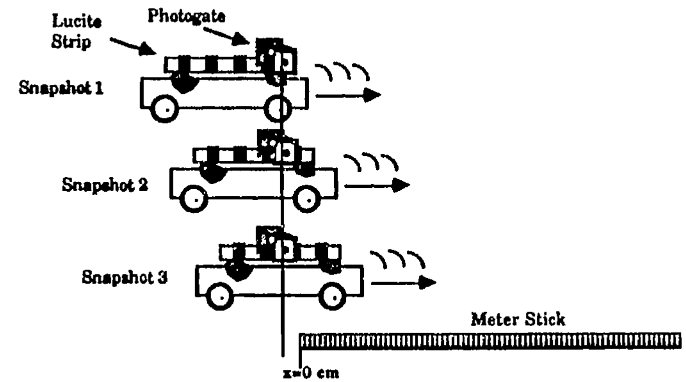
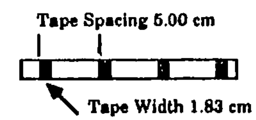


Suppose your classmate had taken photogate data instead to determine the motion of the cart with more precision. Assume that a lucite strip with stripes of tape on it, is mounted on top of the cart. The MBL event timer software is set up to measure the time intervals between when the photogate is blocked and when it is unblocked as each tape passes through the gate. He or she might have recorded the following data for the first two tapes on the lucite strip.

- Width of each tape = 1.83 cm
- Distance from the leading edge of one tape to the leading edge of the next tape = 5.00 cm.



Block Time	Unblock Time	Block Time	Unblock Time
0.000	1.210	2.000	2.338

Note: If you have trouble visualizing this set up, ask the instructor to help you set up a photogate timing system on your computer.

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✍ GE 4-7: Calculating Acceleration from Photogate Timing Data

(a) Use the fundamental definition of average velocity to calculate the average velocities for the two tapes. Show your calculations clearly in the space below.

(b) Use the values you just calculated for the average velocities and the fundamental definition of average acceleration to determine the average acceleration during the time that the tapes pass through the gate. Show your calculations clearly in the space below.

Kinematic Equations for Constant Acceleration

So far you should have concluded that all the falling motions in the lab have resulted in accelerations that are more or less constant while horizontal motions have no acceleration associated with them. There is a standard set of equations that can be derived, using the principles of calculus, that describe motion of an object that undergoes constant acceleration. These equations are called the kinematic equations and they are derived in your text book. By re-examining the graphs you have sketched that describe objects moving with constant acceleration and using the definitions of instantaneous velocity and acceleration, you can derive the kinematic equations.

Notes:

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✍ GE 4-8: Derivation of Kinematic Equations

(a) <u>v as a function of t when the initial velocity is v_0:</u>
Using the fact that $a = dv/dt$ and that the velocity vs. time graphs for "falling" objects or objects rolling on a ramp are a straight line, show that

$$v = v_0 + a\,t$$

(b) <u>x as a function of t when the initial velocity, v_0, is 0:</u>
When you rolled a cylinder down a ramp from resting, its position vs. time graph was a curve. One very simple curve is a parabola in which $x = k\,t^2$. Using the fact that $v = dx/dt$ and the result you just obtained above, you can show that $k=(1/2)a$ so that

$$x = (1/2)\,a\,t^2 \quad \text{when } v_0 = 0$$

Note: Another way to get at this equation is to realize that $v=dx/dt$ and that $a=dv/dt$ so that $a = d^2v/dt^2$. Thus, the validity of the equation can be checked by differentiating x with respect to time twice and seeing if the second derivative is indeed the constant a.

(c) <u>x as a function of t when the initial velocity $v_0 \neq 0$:</u>
When you gave an object an initial velocity by pushing it up and then letting it fall back down a ramp, its position vs. time graph was still a parabolic curve but it was not centered on the origin. Instead it has the form $x = k_1 t + k_2 t^2$. By using the derivative again, show that

$$x = v_0 t + (1/2)\,a\,t^2 \quad \text{when } v_0 \neq 0$$

Note: All the other kinematic equations in the text can be derived by substitution as a combination of the equations in parts (a) and (c).

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Recreating Falling Accelerations by Whacking a Ball

What is the acceleration when a ball rolls freely (without being touched) on a smooth horizontal surface? Can you learn how to whack a ball so that you can recreate the type of acceleration you have observed for a ball rolling down a ramp or falling freely? If so, we can use the similarity between a falling ball and a whacked ball to study projectile motion in which an object falls vertically and moves horizontally at the same time.

To make the one-dimensional measurements described below you will be using a twirling baton with a rubber tip to tap gently on a duck pin ball, which is rather like a small bowling ball. You and a partner should gather the following equipment to study the motion of the ball:

- Duck Pin Ball & Twirling Baton
- Stop Watch
- Tape Measure or Meter Stick
- Chalk (position markers)

Find a stretch of fairly smooth level floor that is about 10 meters long. A hallway is a good bet for this series of measurements. You are to record data for position vs. time for your ball for three different situations: (1) a *briskly* rolling ball receiving no whacks, (2) a ball starting at rest and receiving regular light taps, (3) a ball that has an initial velocity but is tapped lightly and regularly in the direction opposite to its *initial* velocity. Before taking data, you and your partner should practice techniques for making these measurements.

Notes:

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EDGE 4-9: Motion of a Freely Rolling Big Ball

(a) Decide how to take and analyze data for position vs. time for a briskly rolling ball that receives no whacks, so as to determine the acceleration of the ball. For the time being try to ignore the friction that causes the ball to stop eventually. Take, analyze, and display your data and findings. Explain how you took your data and draw conclusions about the acceleration of the ball.

(b) Calculate the average velocity of the freely rolling ball as well as its standard deviation. Use the standard deviation to calculate the *relative* uncertainty in the velocity of the ball if you were to take just one velocity measurement for it as it rolls.

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✍GE 4-10: 1D Tapping of a Big Ball Starting from Rest

Decide how to take and analyze data for position vs. time for a ball that is initially at rest and then receives a series of light whacks. Take, analyze, and display your data and findings. Explain how you took your data and drew conclusions about the acceleration of the ball.

Notes:

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✍GE 4-11: 1D Tapping of a Big Ball w/ Initial Motion

Decide how to take and analyze data for position vs. time for a ball that is initially moving in a direction of tapping and then receives a series of light taps until it stops, turns around, and travels some distance. Try to use the same tapping technique that you used in the previous project. Take, analyze, and display your data and findings. Explain how you took your data and drew conclusions about the acceleration of the ball.

Notes:

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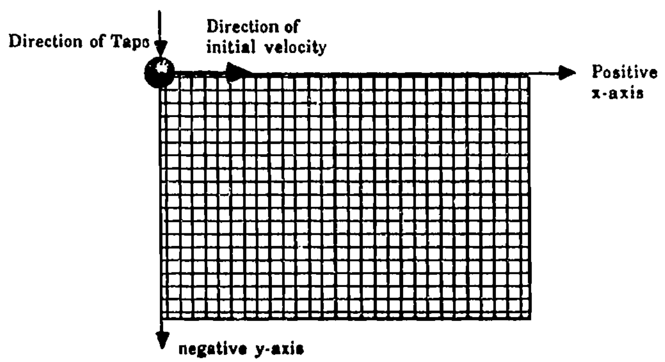
✍GE 4-12: Prediction of Projectile Motion

(a) Suppose you were to roll the ball briskly in one direction as described in GE4-9 and then proceeded to tap on it at right angles to its original direction. Can you guess what the resulting graph of its two-dimensional motion would look like? You can sketch the predicted motion in the graph below. *Please use your previous observations of vertical and falling motion in 1D and of horizontal motion in 1D to make an intelligent prediction of the path followed by the ball and, hence, a projectile.*



(b) Explain the basis for your prediction.

Notes:

SESSION THREE: MEASURING AND ANALYZING 2D MOTION

Determining the Path of a Ball in Two Dimensions
To make two-dimensional measurements described below you will be using the twirling baton and duck pin ball once again. You and a partner should gather the following equipment to study the motion of the ball:

- Duck Pin Ball & Twirling Baton
- Stop Watch
- Tape Measure or Meter Stick
- Small bits of Masking Tape (position markers)
- OPTIONAL: A metronome (or a partner who can clap or sing with a steady rhythm.)

Find a stretch of fairly smooth level floor that is about 10 meters on a side. A gym floor is a good bet for this series of measurements. You are to record data for position vs. time for a ball that has a brisk initial velocity but is tapped lightly and regularly in the direction perpendicular (i.e., at right angles) to its *initial* velocity. Before taking data, you and your partner should practice techniques for making these measurements. Try to use the same tapping technique that you used in the previous project.

Notes:

✍GE 4-13: 2D Tapping of a Big Ball w/ Initial Motion

(a) Record the x and y position of the ball as a function of time and create a data table in the space below. *Be sure to label the quantities in the table and include appropriate units in each header.*

(b) Plot x vs.t and y vs. t using Cricket Graph and discuss how these curves compare with various one-dimensional motions for position vs. time. Affix the graphs in the space below.

(c) Try doing either a simple and/or polynomial fit to each curve. Find the function that fits each curve the best and enter these equations in the space below. Do these best fit functions bear any relationship to the kinematic equations you derived in GE4-8 during the last session?

(d) Enter your data into a spreadsheet with the following columns in it and perform the necessary calculations. Affix it below (you can cover up the list if you like!):

1. time data
2. measured x-value
3. measured y-value
4. calculated magnitude of total displacement,
5. calculated V_x in each time interval
6. calculated V_y in each time interval
7. the speed; i.e., the magnitude of the total velocity

(e) Paste your spreadsheet into Cricket Graph and obtain a graph of y as a function of x. Affix the graph below. What is its shape? How is the graph related to the two-dimensional path of the ball?

This Week's Lab– A Forensic Experiment

A person shoved out of a window makes just as good a projectile as a golf ball rolling off a table. You should read the murder mystery entitled A Damnable Man on the next page. In order to solve the crime you must read the section on projectile motion in your text carefully and discover for yourself what variables might be important in solving the crime. In fact, not all of the information given in the mystery is relevant and some information which you can find for yourself by observation and experiment is missing. Please talk with your classmates and try to determine what measurements might help you solve the crime. The required measurements are not extensive and only require apparatus you have already used in the lab. You should be prepared to come in over the weekend, if needed, to make some measurements.

The Lab Report:

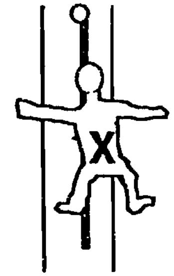
1. It is to be in short format with some additional sections.

2. Include a brief description in your report of the information you think you need in order to solve the case of A Damnable Man . Justify your choices and describe how you might find any missing information.

3. Find the missing information and/or take needed measurements. Report on it and describe how you found this information or took these measurements.

4. Solve the crime, explaining clearly any equations you used or calculations you made.

A Damnable Man



by Kevin Laws

A warm, quiet, humid night in the city -- the traffic has died away and there isn't even a cooling breeze. There is a hotel, a fancy hotel busy inside, but the sounds don't carry through the windows. The hotel has impressively large rooms, obvious from the outside because there is more space between floors and rooms than normal. It looks as if the rooms have 14 foot high ceilings, nice plate glass windows that slide open, and fully two foot-thick floors for ducting and sound insulation. This is the type of hotel that people stay at when someone else is paying the bill.

Outside the hotel, a man is speaking quietly with the doorman, then begins to measure the plush runway carpet for replacement. He is reeling out the tape between the hotel and the curb when a scream breaks the quiet. Looking up, he sees a man falling toward him. Stunned, he drops the tape measure and runs for the safety of the hotel. The doorman stands, horrified, as the man completes his fall with a sickening sound, ensuring that the carpet must be replaced. At intense times, people can think of the strangest things, and the carpet-man finds this to be true . . .all he can think of are the bloodstains left on his tape measure. Even if they are cleaned off, he doesn't think he can use it again without thinking of tonight. Even measuring with another will be hard, and 18 feet will be indelibly marked in his memory -- that's where the blood stains are.

The police arrive and quickly come to the conclusion that it is not a suicide -- among the victim's personal effects, they find pictures and records that indicate he has been blackmailing four other occupants of the hotel. He also has bruises on his shins where the ledge at the bottom of the tall hotel window would have hit them; he must have been pushed pretty hard. Adam Able is the dead man's name, as it appears on the driver's license in his wallet. His license indicates that Adam was 5'11" tall and weighed 160 lbs. He has been blackmailing Adrianna Myers, a frail widow in Room 356; Steven Caine, a newspaper reporter in Room 852; Mark Johnson, a body builder in Room 1956; and Stanley Michaels, an actor in Room 2754. All of the suspects admit they were in their rooms at the time of the murder.

WHO KILLED ADAM ABLE ?

APPENDIX B: Tools for Thinking
Sample MBL Unit on Motion

Tools for Scientific Thinking

Tools for Scientific Thinking is a project of the Center for Science and Mathematics Teaching at Tufts University which uses microcomputer-based laboratory tools to teach physics concepts.

To date, the Tufts' project has produced guided-inquiry units in seven different conceptual areas. These units have been tested for a number of years at eight colleges and universities and at numerous high schools. The approach has been shown to be far more successful than the traditional lecture method in developing an intuition for basic physical concepts. Each unit consists of appropriate hardware, software, and written materials for two to three hour laboratory investigations.

The material on the following pages is a copy of Investigations 4, 5, and 6 from the Introduction to Motion Series.

Micro-Computer Based Laboratory Unit Subject Areas

1. Motion (Kinematics)
2. Force and Motion (Dynamics)
3. Heat and Temperature
4. Simple Harmonic Oscillations (including energy)
5. Sound
6. Visible Light
7. Electricity

Name____________________
Class____________________
Lab Partners____________________

INTRODUCTION TO MOTION-CHANGING MOTION

Investigation 4: Velocity and Acceleration Graphs

To find out
How and when objects accelerate
The meaning of acceleration, its magnitude and direction
The relationship between distance, velocity and acceleration graphs

Materials
Motion disks
motion detector
Red Box interface
cart or toy car
ramp (smooth board or table top)

Introduction
Any time the velocity changes, there is an acceleration. In this investigation you will look at velocity and acceleration graphs for the motion of your body. You will also look at graphs for a cart or toy car rolling on a ramp.

Activity 1 **Speeding Up and Slowing Down**

In this activity you will look at graphs of your motion when you are changing your speed.

1. Go to the Main Menu. Select Motion Grapher and prepare to graph distance and velocity. (Select Collect , Screens and then Split.) A time scale of 5 seconds should work.

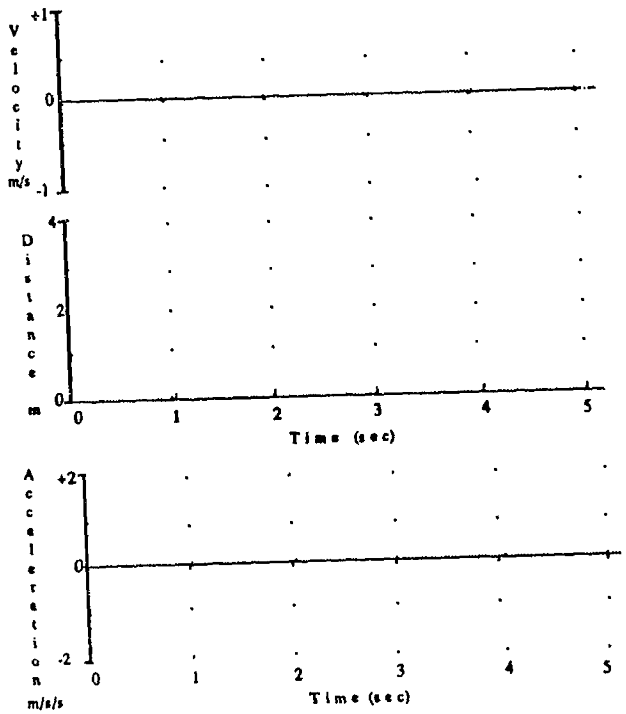
2. Set up the motion detector . You should have a clear path for a distance of about 4 meters in front of the detector.

3. Make distance and velocity graphs starting from rest, walking away from the detector, speeding up and finally stopping short. Plot velocity first. Try to make your motion smooth--not jerky, and keep your body stiff. Take care not to swing your arms.

   Watch your velocity graph as you walk. Try to make it smooth, and to make your increase in speed steady. You may need to repeat your motion several times until you get it right.

Now display the distance. Change the distance and velocity scales if necessary so that the graphs fill the axes. Move your graphs to **Data B** for later comparison, using **Data** and **Move DataA-->B**.

Sketch your distance and velocity graphs below. (Ignore the acceleration axes for now.)



Questions

How does your distance graph differ from the distance graphs for steady (constant velocity) motion which you looked at in earlier investigations?

___

___

What about your velocity graph shows motion *away* from the detector?

___

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What about your velocity graph shows that you were *speeding up*? How would a graph of motion with a constant velocity differ?

___

___

4. Use Screens to display velocity and acceleration. Adjust the acceleration scale so that your graph fills the axes. Sketch your acceleration graph on the acceleration axes on the previous page.

Questions

Your acceleration graph is probably bumpy, since your steps are by nature jerky. During the time that you were speeding up, are the bumps mostly positive or negative? How does *speeding up* while moving *away* from the detector result in this sign of acceleration?

___

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___

Locate the part of your acceleration graph where you were coming to rest. Label it with an arrow. Is the acceleration positive or negative? How does *coming to rest* while moving *away* from the detector result in this sign of acceleration?

___

___

5. Make velocity and acceleration graphs walking toward the detector, moving quickly at first and then slowing down. Start about 4 meters away. Begin as quickly as you can with quick steps, and then gradually decrease your speed. Again try to make your velocity graph as smooth as possible, and to make your decrease in speed steady.

Sketch these graphs on the same velocity and acceleration axes on the previous page. Be sure to label the two sets of graphs as *Away--Speeding Up* and *Toward--Slowing Down*.

Questions

How does your velocity graph show that you were moving *toward* the detector?

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How does your velocity graph show that you were *slowing down*?

___

During the time when you were slowing down, are the bumps of your acceleration graph mostly positive or negative? Explain how *slowing down* while moving *toward* the detector results in this sign of acceleration?

Locate the part of your acceleration graph where you were starting up and beginning to move quickly. Is the acceleration positive or negative? Explain how *speeding up* while moving *toward* the detector result in this sign of acceleration?

Prediction How can you predict the sign of your acceleration if you know the sign of your velocity (ie., your direction of motion) and whether you are speeding up or slowing down? State a general rule.

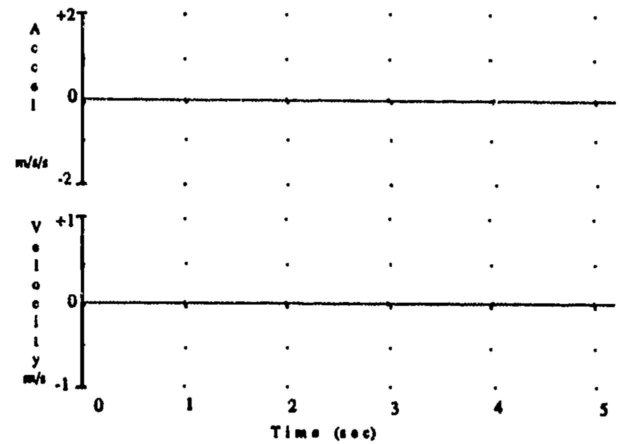
Use your rule to predict the sign of your acceleration if you walk *toward* the detector, starting from rest and then speeding up.

Before you test your prediction, remove your previous graphs using **Clear** and **Data (Hide DataB)**.

6. Make velocity and acceleration graphs starting from rest, walking toward the detector, speeding up and finally stopping short. Start about 4 meters away. As before, try to make your velocity graph as smooth as possible.

   Move your graphs to **Data B** for later comparison, using **Data** and **Move DataA-->B**.

Sketch these graphs on the axes below.



Question During the time when you were speeding up, was your acceleration positive or negative? Did the sign agree with your prediction? Explain how *speeding up* while moving *toward* the detector results in this sign of acceleration.

Prediction If you walk away from the detector, moving quickly at first and then slowing down, will your acceleration be positive or negative?

7. Now test your prediction. Make velocity and acceleration graphs walking away from the detector, moving quickly at first and then slowing down. Make your velocity graph smooth.

   Sketch your velocity and acceleration graphs on the same axes above. Be sure to label the two sets of graphs as *Away--Slowing Down* and *Toward Speeding Up.*

Questions During the time when you were slowing down, was your acceleration positive or negative? Did the sign agree with your prediction? Explain how *slowing down* while moving *away* from the detector results in this sign of acceleration.

Based on all of your observations, was the general rule you predicted about the sign (direction) of the velocity and the sign (direction) of the acceleration correct? If not state a revised, correct version.

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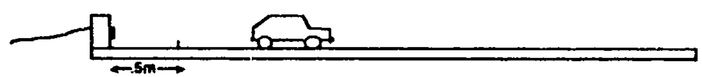
Activity 3 **Graphing Velocity and Acceleration of a Coasting Cart**

1. Set up the motion detector at the end of a board. Use a 2-3 meter long board on the floor or a level table top. The detector should be at one end, aimed toward the other end. Use a distance graph to make sure that the detector can "see" the cart all the way to the end of the board. You may need to tilt the detector up slightly.



Make a mark on the board .5 meter from the front of the detector, and be sure that the starting point of the cart is always beyond this mark.

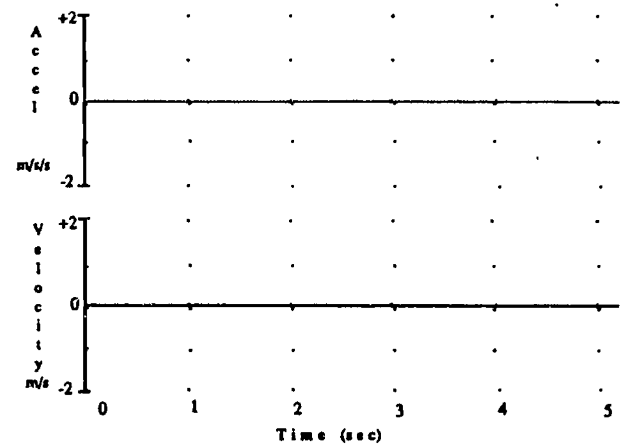
Choose a cart with a significant amount of friction, but with wheels that roll smoothly. Use this same cart throughout the rest of this and the next two investigations.

2. Graph the velocity and acceleration of a cart or toy car coasting on the level track. When you begin to hear the clicks from the motion detector, give the cart a gentle push away from the detector and let it coast to a stop near the end of the track. (Be sure that your hand is not between the car and the detector.

You may have to try a few times to get a good run. Don't forget to change the scales if this will make your graphs clearer.

When you get a good run, move your graph to **Data B.**

3. Neatly sketch your results on the axes below.



Label your graphs with—

"A" at the spot where you started pushing.

"B" at the spot where you stopped pushing.

"C" at the spot where the cart stopped coasting.

Question Is the sign of the acceleration what you expected? Explain.

____

____

Why did the cart stop?

____

4. Graph the velocity and acceleration again. This time, start the cart at the other end of the ramp. Give it a gentle push toward the detector, and let it coast to a stop at least .5 meter in front of the detector.

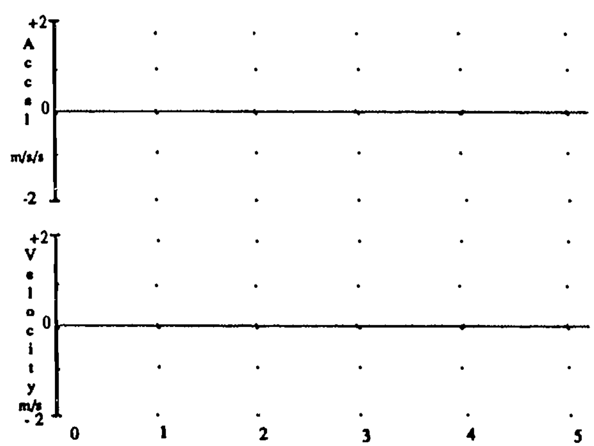
Neatly draw your results on the same axes above. Be sure to label these graphs *Toward Detector* and the earlier graphs *Away from Detector.*

Question In what significant ways do the graphs for motion coasting toward the detector differ from the ones for coasting away from the detector? Explain these differences.

Prediction How would you push the cart to make it move with a steady speed?

Activity 4 **Velocity and Acceleration of a Cart Moving at a Steady Speed**

Graph the motion of the cart on the level ramp again. First clear your previous graphs from the screen. This time, hold the cart and push it so that it moves away from the detector with a constant velocity. Try several times until you get a fairly constant velocity. Sketch your results on the axes below.



Questions Describe how you pushed the cart. Do you think that it took a steady push or a push that changed in some way as the cart moved along?

Why was the push needed to make the cart move with a constant velocity?

Compare the *average* acceleration of the cart to the *average* acceleration whe[n] the cart coasted to rest in Activity 3.

If there were no frictional force, how large a force would be needed to push the cart to keep it going with a constant velocity once it is moving? Explain your answer.

INTRODUCTION TO MOTION--CHANGING MOTION

Investigation 5: Acceleration and Force

To find out
More about velocity and acceleration graphs
How forces affect the motion of objects

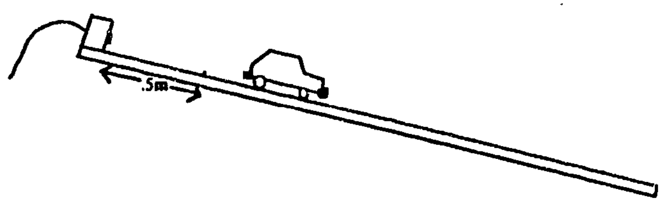
Materials
Motion disks
motion detector
Red Box interface
cart or toy car
tilted ramp (smooth board or tilted table)

Introduction
In the previous investigation you looked at velocity and acceleration graphs for objects with a changing velocity. In this investigation you will look at some more examples of accelerated motion. You also will look a bit closer at what causes acceleration.

Activity 1
A Different Sort of Push

In a previous activity you pushed a cart to make it roll on a level ramp at a constant speed. Here you will produce motion at a constant speed in a different way.

1. Set up the motion detector at the end of a tilted board. Use a long board or a tilted table top. The detector should be at one end, aimed toward the other. Use a distance graph to make sure that the detector can "see" the cart all the way to the end of the board.



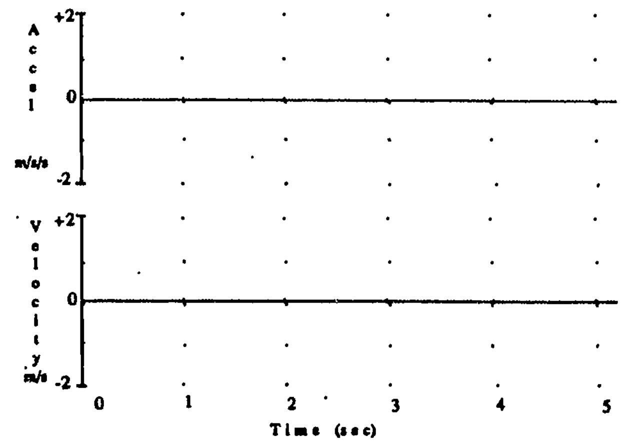
Make a mark on the board .5 meter from the front of the detector, and be sure that the starting point of the cart is always beyond this mark.

2. Prepare to graph velocity and acceleration. A time scale of 5 seconds should work.

3. Graph velocity and acceleration of the cart rolling down the tilted ramp at a steady (constant) velocity away from the detector. You will probably need to give the cart a little push to get it rolling. Adjust the tilt of the ramp

carefully until the velocity of the cart is constant. This will probably take many tries.

When the motion is nice and steady, and you are satisfied with your graphs, adjust the velocity and acceleration scales so that your graphs fill the axes. Sketch the velocity and acceleration neatly on the axes below

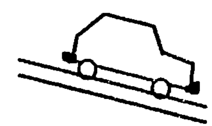


Questions
Compare your graphs to those in the previous investigation for motion of the cart *at a steady (constant) velocity* on the level ramp. Are the graphs similar in shape? Would you expect them to be similar? Why or why not?

____

____

What forces are acting on the cart as it rolls down the ramp? Draw these in on the diagram, and describe each one below.



____

____

Which force is equivalent to your push in the previous investigation?

____

How would the motion and graphs be different if there were no friction?

Activity 2 **Velocity and Acceleration of a Cart that is Speeding Up**

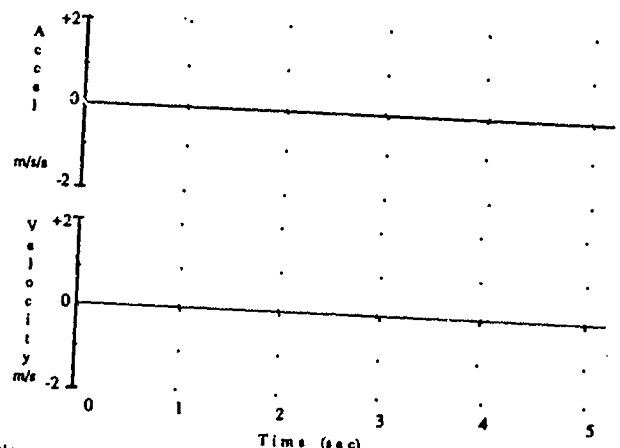
1. Graph the cart rolling down the ramp and speeding up. Tilt the ramp more so that the cart speeds up as it rolls down. Let the cart start from rest. Graph velocity and acceleration. Be sure that you start the cart beyond the .5 meter mark.

   Try to release the cart as soon as you hear clicking noises from the motion detector.

2. Save your data to disk for analysis in the next investigation. **Esc** to the Options Menu. Then select **Disk** and **Save Data A**. Name your data with your initials followed by **ACT2**. Then press **Return** to save. **Return** and **Esc** return you to the Options Menu.

3. Move your graphs to Data B. Use **Data** and **Move Data A-->B**.

4. After you have adjusted the scales, sketch your graphs neatly on the axes below.

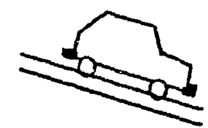


Questions How does your velocity graph differ from that for motion at a constant velocity in Activity 1?

How does your acceleration graph differ from that for motion at a constant velocity in Activity 1?

Explain how the shape of your acceleration graph and the sign of the acceleration describe the motion you observed.

What forces are acting on the cart as it rolls down the ramp after the push? Draw these in on the diagram.



Prediction How would your velocity and acceleration graphs be changed if the ramp were even steeper?

Activity 3 **Speeding Up Even More**

Graph the velocity and acceleration of the cart rolling down a steeper ramp. Again release the cart from rest. Sketch your results on the same axes above. **Be sure to label these graphs as *Steeper*.**

When you are done, save these graphs, named with your intitials followed by **ACT3**. Then move them to **Data B** for comparison in the next two activities.

Questions Did the changes in the velocity graph agree with your predictions? Explain why making the ramp steeper resulted in these changes.

Did the changes in the acceleration graph agree with your predictions? Explain why making the ramp steeper resulted in these changes.

How does a velocity-time graph show that the cart is accelerating?

How does a velocity-time graph show that the acceleration is steady (constant)?

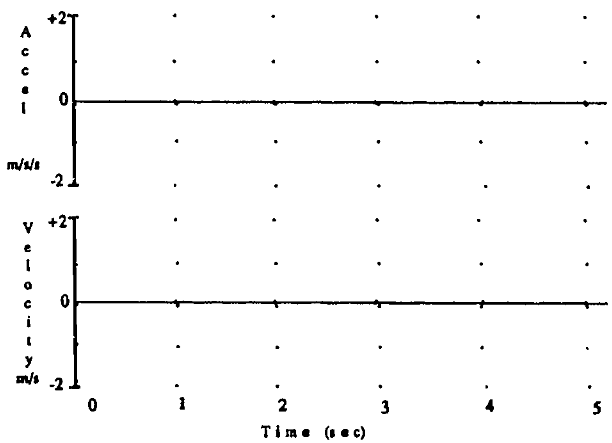
How does an acceleration-time graph show that the cart is accelerating?

Activity 4 **Once a Push, Always a Push?**

1. Graph the cart rolling down the tilted ramp again. Keep the same tilt as in Activity 3. This time give the cart a little push to start it rolling. Again start it just when you hear the detector noises. Be sure your hand is not between the detector and the cart when you push it.

2. Sketch these graphs on the axes below. Also sketch the graphs from Activity 3 for motion down the same ramp starting from rest (**Data B**). (Leave the graphs in **Data B** for comparison in the next activity.)

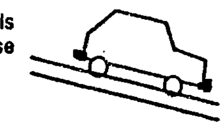
   Indicate with an arrow the point where the push stopped. Be sure to label your graphs *With push* and *Without push.*



Questions How does the acceleration *after you stopped pushing* compare to the acceleration in Activity 3 when the cart started from rest without a push? Is one larger or are they about the same?

Does the push appear to have any effect on the acceleration *after you stop pushing*? On the velocity? Explain.

What forces are acting on the cart as it rolls down the ramp after the push? Draw these in on the diagram.



Activity 5 **Graph the Motion of a Cart Rolling Up and Down a Ramp**

Making a cart accelerate down a steep track is similar to dropping a ball from a height. In this activity, you will give the cart a push *up* the ramp and let it return. This is similar to throwing a ball straight up in the air.

Predictions You throw a ball straight up in the air. What is the velocity at the moment that the ball reaches its highest point and is about to start back down? At this moment, is the acceleration positive, negative or zero? (Assume that the positive direction is *upward.*)

Velocity: ______________ Acceleration: ______________

If you give the cart a push up the ramp and release it, what will the velocity be at the moment that the cart reaches its highest point and is about to start back down? At this moment, is the acceleration positive, negative or zero. (Assume that the positive direction is *down* the ramp--away from the detector.)

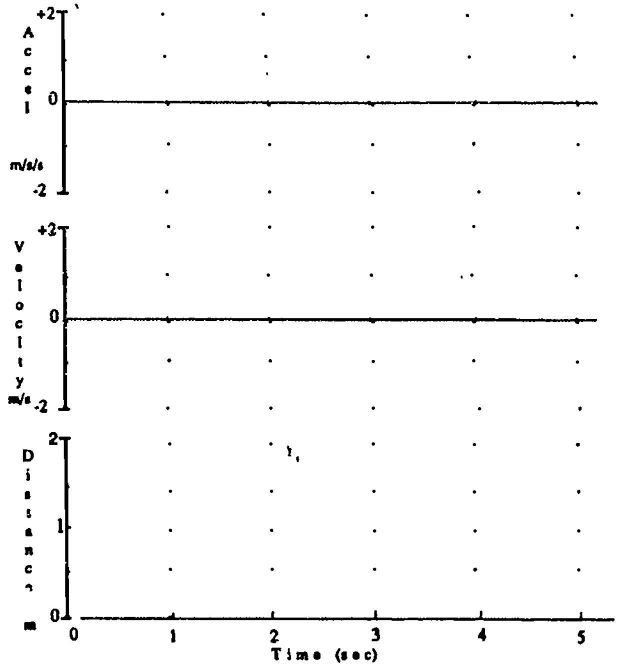
Velocity: ______________ Acceleration: ______________

Now test your predictions. Leave the graphs from Activity 3 in **Data B**. Leave the ramp and detector set up exactly as in Activities 3 and 4.

1. Graph the distance and velocity of the cart rolling up and down the ramp. Start the motion just when you begin to hear the detector clicking. Give the cart a push up the ramp and release it.

2. When you get a good run, sketch both graphs on the axes on the next page. *Do not use a run where the cart came closer than 0.5 meters to the detector.*

   Use **Screens** to display velocity and acceleration, and sketch the acceleration. Make sure all three graphs are correctly placed on the time axis.



Questions

Label *all three* graphs with—

"A" where the cart started being pushed.

"B" where the push ended (where your hand left the cart).

"C" where the cart reached the top (and is about to start down).

"D" where the cart reached the bottom again

Explain how you know where each of these points is.

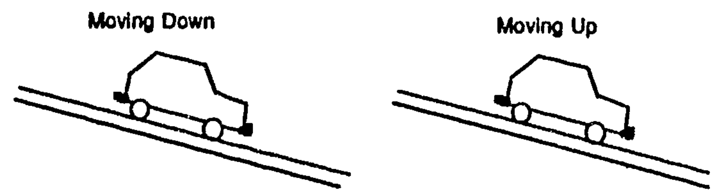
Did the cart stop at the top? (Hint: Look at the velocity graph.) Does this agree with your prediction? How much time did it spend at the top before it started back down? Explain.

According to your acceleration graph, what is the acceleration at the instant the cart reaches the top? Does this agree with your prediction? Explain.

On the way back down, is there any difference between these velocity and acceleration graphs and the ones in **Data B** produced by the cart rolling down from rest (Activity 3)? Explain.

Compare the average acceleration of the cart on the way up (but after you stopped pushing) and on the way down (but before reaching the bottom). Are they the same? Base your answers on your velocity and acceleration graphs.

On the diagram below, draw in the forces acting on the cart on the way up the ramp (after the push) and on the way down the ramp. Does any force have a different direction on the way up than on the way down?



Explain any differences in the acceleration going up and coming down in terms of the forces on your diagram.

INTRODUCTION TO MOTION--CHANGING MOTION

Investigation 6: Measuring Acceleration

To find out How to determine acceleration quantitatively from velocity and acceleration graphs

Materials *Motion* disks with data from Investigation 5

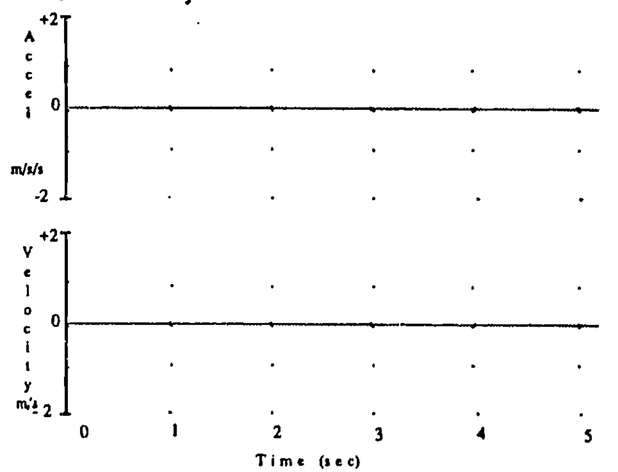
Introduction In this investigation you will analyze the motion of a cart rolling down a tilted ramp. You will determine the cart's acceleration from your velocity and acceleration graphs.

Activity 1 **Velocity and Acceleration of a Cart That Is Speeding Up**

1. Load the data for the cart rolling down the tilted ramp (Investigation 5/Activity 2) into Data A. Select **Disk** from the Options Menu, then **Load DataA.** Select the data labeled with your initials and **ACT2**, press **Return** (and then **Y** if there are already data in A).

   Display velocity and acceleration, and adjust the axes if necessary.

2. Sketch the velocity and acceleration graphs below. Correct the scales if necessary.



3. Calculate the average acceleration of the cart from your acceleration graph. Use the **Graphics-cursor** in **Analyze** on the Options Menu to read values from the acceleration graph.

Read a number of values (say ten) of the acceleration, equally spaced in time. (Only use values from the portion of the graphs after the cart was released and before it reached the bottom of the ramp.)

Calculate the average value of the acceleration.

Accelerations from graph (m/s^2): _____ _____ _____ _____ _____
_____ _____ _____ _____ _____

Average acceleration (mean): ________ m/s^2

Comment Average acceleration during a particular time period is the change in velocity divided by the change in time. This is the average rate of change of velocity. By definition, the rate of change of a quantity graphed with respect to time is also the slope of the curve. Thus the (average) slope of an object's velocity-time graph is the (average) acceleration of the object.

4. Calculate the average acceleration from your velocity graph. Calculate the slope of your velocity graph. Use the **Graphics Cursor** in **Analyze** to read the velocity and time coordinates for two typical points on the velocity graph. For a more accurate answer, use two points as far apart in time as possible but still during the time the cart was moving.

   Point 1 Velocity _______ m/s Time ________ sec

   Point 2 Velocity _______ m/s Time ________ sec

   Calculate the change in velocity between points 1 and 2. Also calculate the corresponding change in time (time interval). Divide the change in velocity by the change in time. This is the *average* acceleration. Show your calculations below.

Change in velocity: _______ m/s

Time interval : _______ sec

Average acceleration : _______ m/s^2 **(Speeding Up)**

Questions

1. Is the acceleration positive or negative? Is this what you expected?

____

2. Does the average acceleration you just calculated agree with the average acceleration you calculated from the acceleration graph? Do you expect them to agree? How would you account for any differences?

____

____

Activity 2 Speeding Up Even More

1. Load the data for the cart rolling down the more tilted ramp (Activity 3) into Data B. Select **Disk** from the Options Menu, then **Load DataB.** Select the data labeled with your initials and **ACT3**, press **Return** (and then Y, if necessary).

   Display velocity and acceleration.

2. Sketch the velocity and acceleration graphs. Use dotted lines on the axes above.

3. Calculate the average acceleration of the cart from your acceleration graph. Use **Analyze** as before to read acceleration values.

   Calculate the average value of the acceleration.

Accelerations from graph (m/s^2): _____ _____ _____ _____ _____

_____ _____ _____ _____ _____

Average acceleration (mean): ________m/s^2

4. Calculate the average acceleration from your velocity graph.
   Calculate the slope of your velocity graph. Use **Analyze** as before to read the velocity and time coordinates for two typical points. Remember to use two points as far apart in time as possible.

Point 1	Velocity _______ m/s	Time ________ sec
Point 2	Velocity _______ m/s	Time ________ sec

Calculate the *average* acceleration.

Change in velocity: _______ m/s

Time interval : _______ sec

Average acceleration : _______ m/s^2 (Speeding Up Even More)

Questions

1. Does the average acceleration you just calculated agree with the average acceleration you calculated from the acceleration graph? How would you account for any differences?

   ____

   ____

2. Compare this average acceleration to that with the track less tilted (Activity 2). Which is larger? Is this what you expected?

   ____

   ____

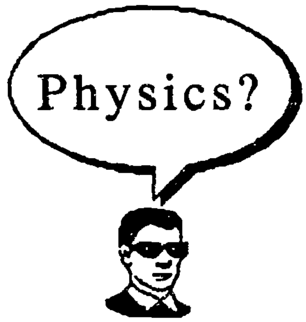
APPENDIX C

Workshop Physics Schedule v2 9/11/89

Physics 131, Fall 1989

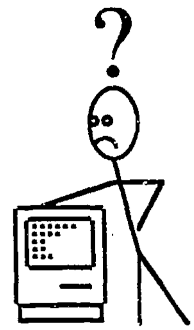
Dickinson College

Robert Boyle and Priscilla Laws w/ Desmond Penny



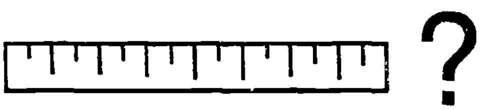
Aug 30
Sep 1

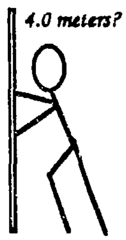
Week 1: Introduction and Computing



Sep 4
Sep 6
Sep 8

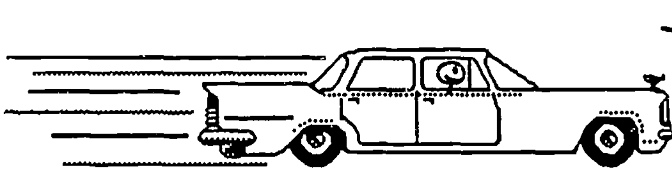
Week 2: Measurement and Uncertainty





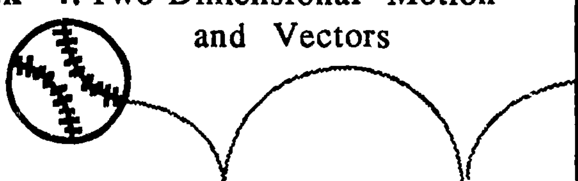
Sep 11
Sep 13
Sep 15

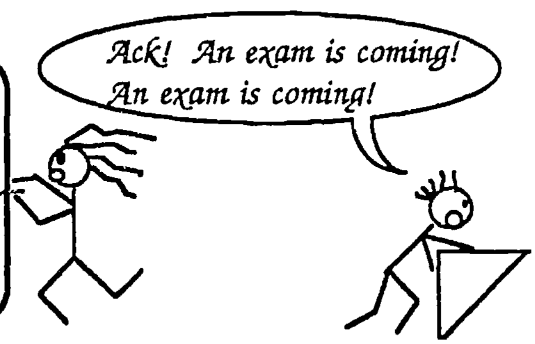
Week 3: One-Dimensional Motion



Sep 18
Sep 20
Sep 22

Week 4: Two-Dimensional Motion and Vectors





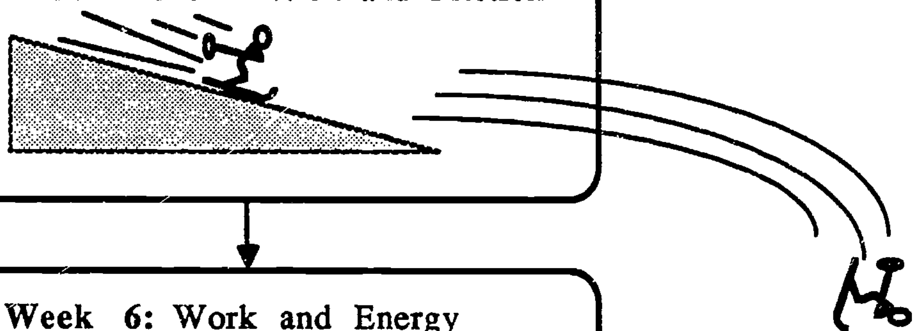
Sep 25
7 pm

EXAM I

Monday, September 25

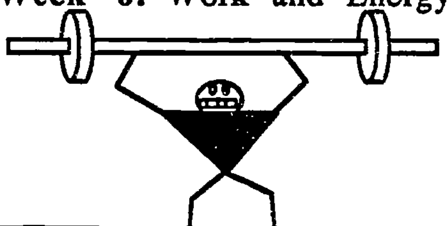
Sep 25
Sep 27
Sep 29

Week 5: Laws of Motion and Friction



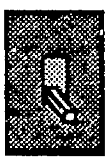
Oct 2
Oct 4
Oct 6

Week 6: Work and Energy

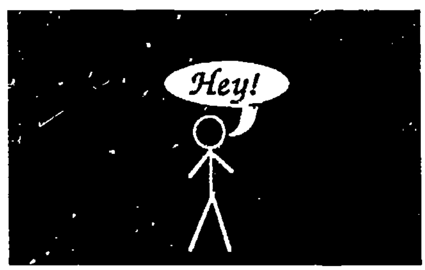


Oct 9
Oct 11

Week 7: Energy Conservation



Turn lights off
when not in use



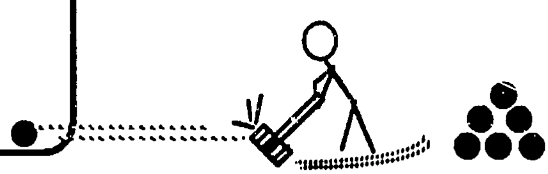
Oct 13

EXAM II

Friday, October 13

Oct 16
Oct 18

Week 8: Particle Systems and Momentum

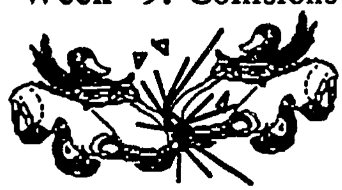


Oct 20

Fall Break

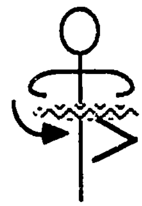
Oct 23
Oct 25
Oct 27

Week 9: Collisions



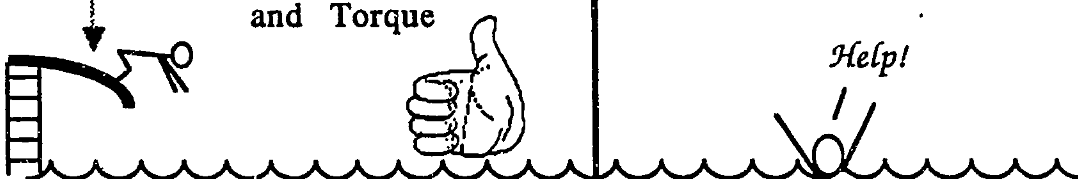
Oct 30
Nov 1
Nov 3

Week 10: Rotation



Nov 6
Nov 8

Week 11: Angular Momentum and Torque



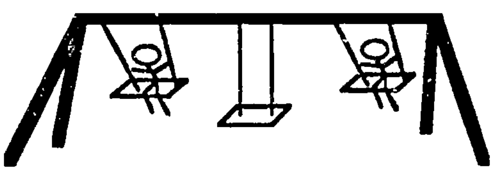
Nov 10

EXAM III

Friday, November 10

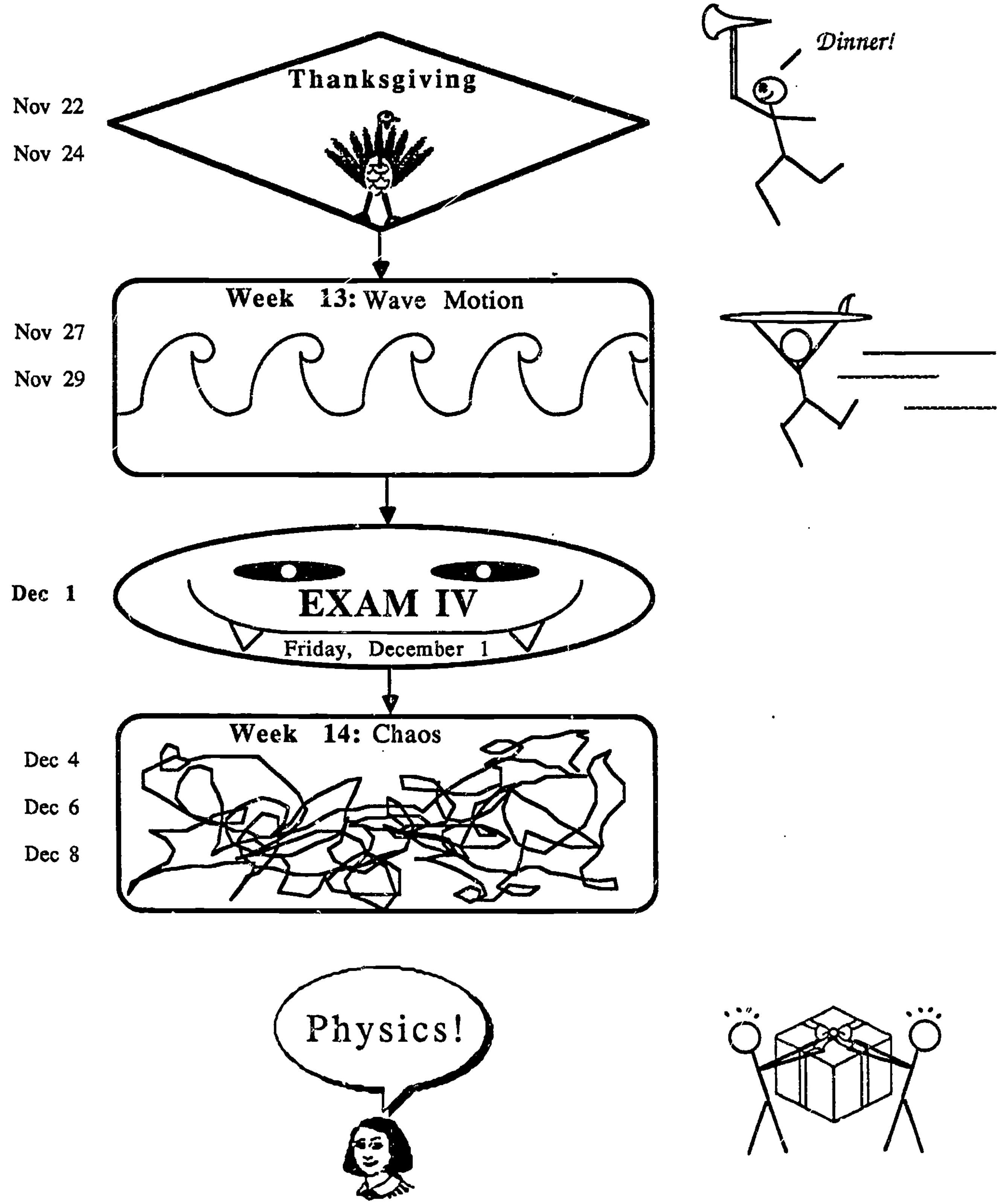
Nov 13
~~(Nov 15)~~
Nov 17
Nov 20

Week 12: Harmonic Motion



Participate in Declare Day on Weds!!!!

73


Dinner!
Nov 22
Nov 24
Thanksgiving
Nov 27
Nov 29
Week 13: Wave Motion
Dec 1
EXAM IV
Friday, December 1
Dec 4
Dec 6
Dec 8
Week 14: Chaos
Physics!

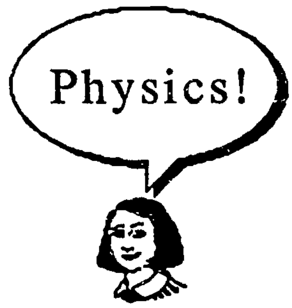
Workshop Physics Schedule

Physics 132, Spring 1989

Dickinson College

Robert Boyle and Priscilla Laws

Picking up right where we left off...



Unit 15: Temperature

Jan 25

Jan 27

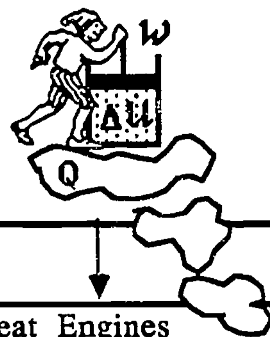
-273°

Unit 16: First Law of Thermodynamics

Jan 30

Feb 1

Feb 3

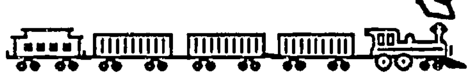


Unit 17: Heat Engines

Feb 6

Feb 8

Feb 10



Formal Lab due Monday, February 13

Feb 13
Feb 15

Unit 18: Second Law of Thermodynamics

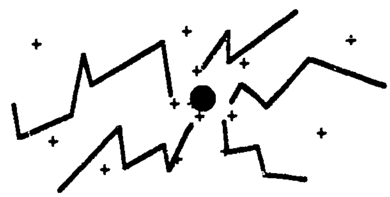
Feb 17

EXAM I

Friday, February 17

Feb 20
Feb 22
Feb 24

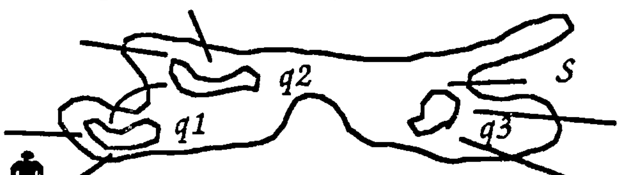
Unit 19: Electric Fields



Formal Lab due Monday, February 27

Feb 27
Mar 1
Mar 3

Unit 20: Gauss' Law



Attend Lecture, 7 pm, March 1, Dana 110

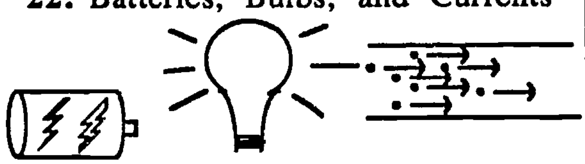
Mar 6
Mar 8
Mar 10

Unit 21: Gravitational & Electrical Potential

Formal Lab due Monday, March 13

Mar 13
Mar 15

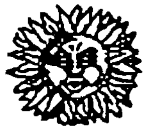
Unit 22: Batteries, Bulbs, and Currents

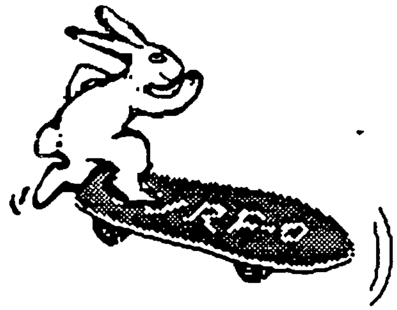


Mar 17 — **EXAM II**

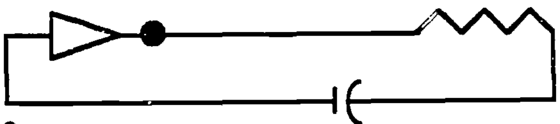
Friday, March 17

Mar 20
Mar 22
Mar 24 — **Break**





Mar 27
Mar 29
Mar 31 — **Unit 23: Direct Current Circuits**



Attend Lecture, 8 pm, March 30, Weiss Center

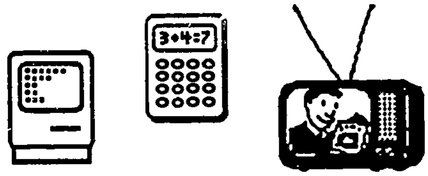
Apr 3
Apr 5
Apr 7 — **Unit 24: Capacitors and Circuits**

Apr 7 — **EXAM III**

Friday, April 7

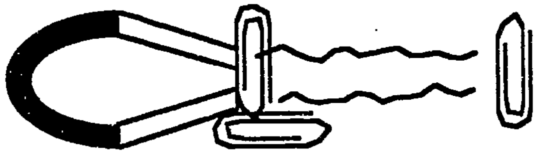
Apr 10
Apr 12
Apr 14

Unit 25: Electronics



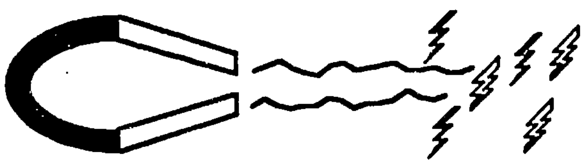
Apr 17
Apr 19
Apr 21

Unit 26: Magnetic Fields



Apr 24
Apr 26

Unit 27: Electricity and Magnetism



Apr 28

EXAM IV

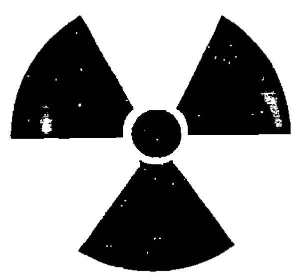
Friday, April 28

May 1
May 3
May 5

Unit 28: Radioactivity and Radon

Rn

Formal Lab due Monday, May 8



Physics!!

APPENDIX D

Workshop Physics: Replacing Lectures with Real Experience

Priscilla W. Laws
Department of Physics and Astronomy, Dickinson College, Carlisle, PA 17013

We are suffering from an uncontrollable burgeoning of knowledge in virtually all disciplines. Nowhere is this more apparent to us than in the grand enterprise we call physics, where whole new areas of theory, application, and investigative technology have flourished in the past decade. As teachers we are challenged to learn and teach fundamentally new theories to describe physical phenomena. Do we understand relativity and quantum mechanics well enough to explain them to introductory physics students? How about chaos, super strings, superconductivity, and the big bang?

Unfortunately, the question of what to teach in introductory physics courses is not the only question confronting us. The issue is not simply what to teach, but how to teach. There is an endless array of new computer-based instructional media, including computer-programming languages, integrated software packages, tutorials, simulations, electronic-mail conferencing, and microcomputer-based sensors. Other new instructional tools include video tapes, interactive videodiscs, and satellite conferencing. We have also developed new understandings about student preconceptions and naive problem-solving strategies. The classroom applications of these new understandings about the learning process constitute part of the growing body of instructional technology, even when they don't involve new hardware.

The desire to cover new ground and use new technology presents us with too many choices—relativity, quantum theory, and chaos versus Newton's laws and classical thermodynamics; new teaching methods based on cognitive theories versus nineteenth-century pedagogy; the digital computer versus the electronic calculator.

The problem of having too many choices has already led us to the creation of the 1,000 page introductory text book. Students complete introductory courses in such a state of cognitive overload that all they retain are a few memorized definitions and algorithms for solving standard textbook problems. The mounting pressure to substitute more contemporary topics for the classical ones runs counter to pleas from physics educators and cognitive psychologists to offer students more concrete experience before dealing with weird, abstract theories about things that don't constitute part of everyday reality.[1]

The syndrome of cognitive overload is rooted in the presentation of far too many topics, the more contemporary of which represent major paradigm shifts away from the basic worldview of classical physics. To adapt a familiar phrase, taking introductory physics is like trying to take a drink from a fire hose.

We are in an exciting period of experimentation with course objectives, content, and pedagogy in introductory physics. We may emerge from this period in the history of physics education with a new intellectual canon that sweeps the nation and eventually the world.[2] On the other hand, the accelerating evolution of the fields of physics and physics teaching may force us to abandon the present uniformity of content and teaching methods for endless experimentation with a host of new approaches.

Workshop Physics: Its Premises

The Workshop Physics project at Dickinson College represents one of a growing number of attempts to forge a new canon or intellectual tradition for introductory physics instruction.[3] Those of us on the Workshop Physics staff[4] want to share our experience with the new approach, but not because it represents the only viable one. Instead, Workshop Physics represents one attempt to address some of the generic problems with introductory physics. Workshop Physics applies recent educational research to the introductory physics curriculum, and it facilitates this application with computer technology. A number of observations and assumptions have guided the development of Workshop Physics.

Reducing Content and Emphasizing the Process of Scientific Inquiry

In developing Workshop Physics we assumed that acquiring transferable skills of scientific inquiry is more important than problem solving or acquiring descriptive knowledge about physics. Arons refers to the acquisition of transferable skills as a way of developing "enough knowledge in an area of science to allow intelligent study and observation to lead to subsequent learning without formal instruction."[5] There were two major reasons for the emphasis on inquiry skills based on real experience. First, most students enrolled in introductory physics at both the high school and college level, do not have sufficient concrete experience with everyday phenomena to comprehend the mathematical representations of them traditionally presented in introductory courses. The processes of observing phenome-

na, analyzing data, and developing verbal and mathematical models to explain observations afford, students an opportunity to relate concrete experience to scientific explanation. A second equally important reason for emphasizing the development of transferable skills is that a student who is confronted with the task of acquiring an overwhelming body of knowledge must learn some things thoroughly and acquire methods for independent investigation to be implemented as needed. This follows Phil Morrison's adage, "Less is more."

Emphasis on Directly Observable Phenomena

The guiding principle for retaining topics in introductory physics is that they be amenable to direct observation and that the mathematical and reasoning skills needed to analyze observations be applicable to many other areas of inquiry. In choosing topics, we should emphasize the development of operational definitions and empirical relationships before introducing formal definitions and theoretical relationships.[6] We approve of the trend toward motivating students with applications of classical physics to problems of current concern. Jearl Walker's expositions of the physics of everyday phenomena, the physics of human motion, and Newtonian cosmology are splendid examples of contemporary applications of classical physics.[7] We do not consider it advisable to add topics such as relativity, quantum mechanics, and chaos. Such topics require levels of abstract reasoning we believe to be beyond the abilities of beginning students.

Eliminating Formal Lectures

Although lectures and demonstrations are useful alternatives to reading for transmitting information and teaching specific skills, no one has ever proved that they are efficient vehicles for helping students learn how to think, conduct scientific inquiry, or acquire real experience with natural phenomena.[8] In fact, some educators believe that peers are often more helpful than instructors in facilitating original thinking and problem solving.[9] The time now spent by students passively listening to lectures is better spent in direct inquiry and discussion with peers. The role of the instructor is to help create the learning environment, lead discussions, and engage in Socratic dialogue with students.

Using the Microcomputer as a Flexible Tool

When used as flexible tools for collecting, analyzing, and displaying data graphically, computers can accelerate the rate at which students can acquire data, abstract, and generalize from real experience with natural phenomena. The digital computer is an essential tool for any inquiry-based learning experience in physics because it has become the most universal tool of inquiry in scientific research. The computer has had a profound effect on the nature and scope of physics research. However, even computer-aided inquiry takes time, and we believe that students cannot engage in the process of guided inquiry and direct observation, even armed

with computers, and still cover the amount of material normally introduced in an introductory physics course sequence.

Workshop Physics: Its Practice

Workshop Physics was first taught at Dickinson College during the 1987–88 academic year to students in both the calculus- and noncalculus-based courses. It is taught in three two-hour sessions each week. There are no formal lectures. The course content in Workshop Physics is about 30 percent less than in our traditional courses. Each section has one instructor, two undergraduate teaching assistants, and up to 24 students. Each pair of students share the use of a Macintosh computer and an extensive collection of scientific apparatus and other gadgets. Among other things, students pitch baseballs, whack bowling balls with rubber hammers,[10] pull objects up inclined planes, attempt pirouettes, build electronic circuits, explore electrical unknowns, ignite paper with compressed gas, and devise engine cycles using rubber bands. The workshop labs are staffed during evening and weekend hours with undergraduate teaching assistants.

The material is broken up into units lasting about one week, and students use an "Activity Guide," which has expositions, questions, and instructions as well as blank spaces for student data, calculations, and reflections. The "Activity Guide" is keyed to a standard textbook. Textbooks that have been used in the calculus-based section include Serway's *Physics for Scientists and Engineers* and Halliday and Resnick's *Fundamentals of Physics*. The noncalculus section uses Faughn and Serway's *College Physics*.[11] In general the curriculum emphasizes the four-part learning sequence described by cognitive psychologist David Kolb.[12] Students often begin a week by examining their own preconceptions; then they make qualitative observations. After some reflection and discussion, the instructor helps them develop definitions and mathematical theories. The week usually ends with quantitative experimentation centered on verification of mathematical theories.

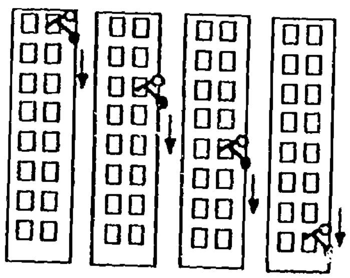
The Role of the Computer in Workshop Physics

The computer is used in almost every capacity except that of computer-assisted instruction. Although the M.U.P.P.E.T. project at the University of Maryland has reported great success at teaching introductory students to program in Turbo Pascal,[13] our attempts to incorporate programming into the introductory lab at Dickinson, led us to feel that we were using physics to teach computing rather than the other way around. We therefore use spreadsheets as the major tool for calculation.

Linearization with Spreadsheets and Graphing

The most popular use of spreadsheets involves entering data directly into the spreadsheet in Microsoft *Works* on the Macintosh SE computer for analysis and

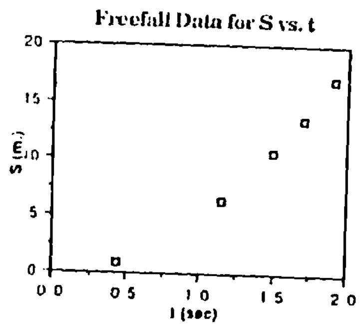
eventual graphing with the *Cricket Graph* software package. Linearization is considered to be one of the essential transferable skills associated with Workshop Physics. Using the microcomputer for linearization and least-squares analysis, students discover simple functional relationships empirically or verify mathematical theories. An unusual application of linearization involves a project in which students poke nails through insulation board to create a parallel array of "flux lines." Students then count the number of nails passing through a wire hoop (representing a surface area) to compare the angle of the hoop's normal vector with the direction of the nails. A graph of the number of nails versus cos θ allows students to discover that $\Phi = E \cdot A = E A \cos \theta$. A simple linearization and graphing exercise is illustrated in Figure 1.



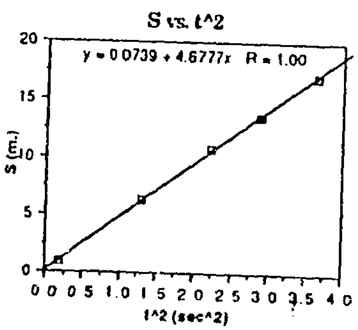
(a) An object is dropped from different heights.

	A	B	C
1	S	t	t^2
2	(m.)	(sec.)	(sec^2)
3	0.82	0.44	0.19
4	6.32	1.15	1.32
5	10.71	1.49	2.22
6	13.55	1.70	2.89
7	17.01	1.91	3.65

(b) The data is entered into a spreadsheet and calculations are performed. This takes a minute or so of a student's time.



(c) The Data is transferred to Cricket Graph™ and plotted. The parabolic curve indicates that S is proportional to t^2. This takes another minute or so of a student's time.



(d) S is plotted as a function of t^2, and the curve is linearized. The slope of 4.68 m/s (which represents the "best estimate" for $g/2$) is derived from a built in least squares analysis.

Figure 1. Lineariz‑‑g data with spreadsheet and graphing software.

Calculations and Modeling with Spreadsheets and Graphing

Spreadsheet calculations are also used instead of integration as a tool to solve numerical problems. In some cases spreadsheet calculations are used for mathematical modeling. For example, spreadsheet relaxation calculations work beautifully for modeling the pattern of electrical potentials surrounding the "electrodes" on electric-field-mapping paper. Mathematical functions representing traveling waves can be plotted in position space at three different times, and the velocity of the wave can be measured on the graph. This helps students explore the real meaning of the expression $y = f(x \pm vt)$.

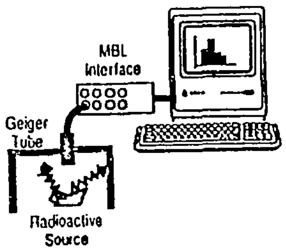
Microcomputer-Based Laboratory Tools

The so-called MBL tools are used extensively to collect, analyze, and display data. An MBL station consists of a sensor or probe plugged into a microcomputer via an electronic device known as an interface. With appropriate software the computer can perform instantaneous calculations or produce graphs. Sensors that have been linked directly to the computer include the ultrasonic motion detector, photogates, temperature sensors, and geiger tubes. In cases where the user can observe or control changes in a system directly, the microcomputer can be set up to display a real-time graph of system changes. Ron Thornton and others have demonstrated that using MBL to create real-time graphs helps students develop an intuitive feeling for the meaning of graphs and for the characteristics of the phenomena they are observing qualitatively.[14] We have found that a time trace of the position of the student's own body is unparalleled as a tool for learning how the abstraction known as a graph can represent the history of change in a parameter. The real-time frequency distribution that can be produced by using the geiger tube with a radioactive source affords the student the same kind of opportunity to explore and develop intuitive notions about both the meaning of frequency distributions and the nature of counting statistics. A simple counting statistics exercise is illustrated in Figure 2.

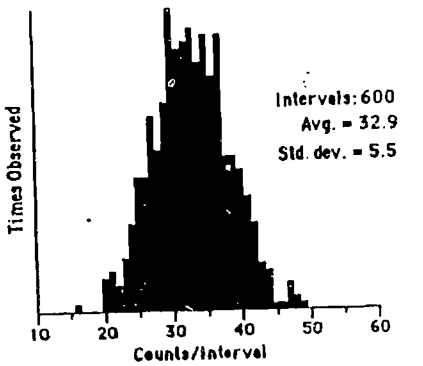
The funding for Workshop Physics has allowed us to develop an interface to link MBL sensors including the geiger tube and the photogate to the Macintosh computer. Some of this development has been coordinated with related projects at Tufts University and Technical Education Research Centers.[15] The photogate software is pedagogically oriented and utilizes a raw plotter to allow students to see the times when one or more photogates are switched on or off by real events. The real-time raw plot, which is one of Robert Tinker's many innovative ideas, encourages students to discover for themselves how to use operational definitions in the measurement of velocity and acceleration. A simple photogate timing exercise with raw plotting is illustrated in Figure 3.

Simulations

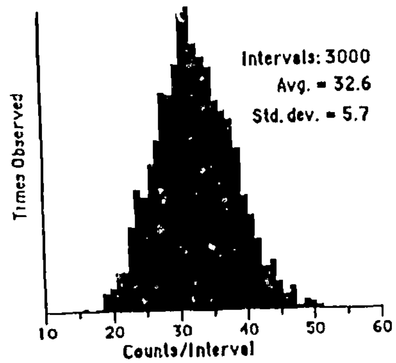
In select cases where acquiring real data is not feasible or is too time consuming, we have resorted to simulations. David Trowbridge's program simulating posi-



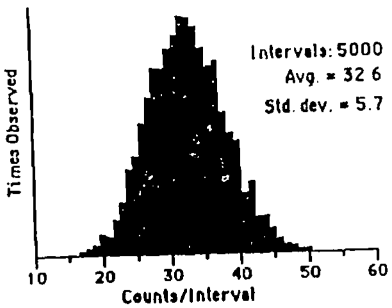
(a) MBL based nuclear radiation counting system for the Mac Computer.



(b) Snapshot of a real time frequency distribution for 600 counting intervals. Rough! (Not to scale)



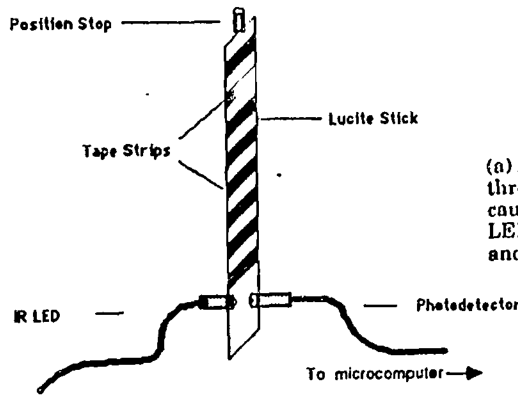
(c) Snapshot of a real time frequency distribution for 3000 counting intervals. Getting smoother! (Not to scale)



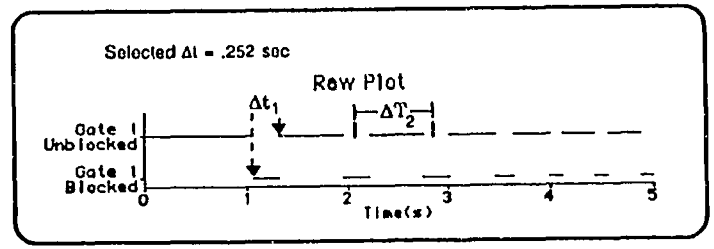
(d) Snapshot of a real time frequency distribution for 5000 counting intervals. Smoothest! (Not to scale)

Figure 2. MBL radiation detection for the study of counting statistics.

tion, velocity, and acceleration graphs for a ball rolling down a set of inclined ramps is one such simulation.[16] Eric Lane's simulation of wave interference is another.[17] A third is the display of electric field lines from a collection of charges developed by Blas Cabrera in a program called *Coulomb*. In *Coulomb* students enjoy creating strange and unique charge configurations on the computer screen and watching the patterns generated by the field lines. This simulation allows stu-



(a) A lucite picket is dropped through a photogate system causing the IR light from the LED to be alternately blocked and unblocked.



(b) A raw plot, showing times at which blocking and unblocking of the gate occur, appears in real time on the microcomputer screen. The raw plot concept was developed by Robert Tinker of Technical Education Research Centers. Once an experiment is complete students can move cursors and determine time intervals between various events of interest.

$\overline{v1}$ = tape width/Δt_1	$\overline{a1} = (\overline{v2} - \overline{v1}) / \Delta T_1$
$\overline{v2}$ = tape width/Δt_2	etc.

(c) Novice students can use operational definitions of velocity and acceleration to determine the rate of fall of the lucite picket through the photogate.

Figure 3. Measuring acceleration with photogate timing.

dents to discover that in two-dimensional Cabreraland, the flux enclosed by a loop is always proportional to the net charge enclosed by the loop.[18]

Desk-Top Publishing

Since written communication skills are considered important, students are required to hand in several formal lab reports each semester. Students use the com-

puter for word processing and creating apparatus drawings for formal laboratory reports. Students augment the word processing program from the Microsoft *Works* package with diagrams created using *MacDraw*.

Conclusions

Although computers served a vital role in the Workshop Physics program, the central focus of the program is on direct experience-based instruction, not computers. Thus we'd like to think the program could survive without computer. Still, the availability of a computer system for every pair of students is heady wine. We are just beginning to explore the full potential of classroom computing, but every time we design a better approach, another new computer technology beckons.

Our first year of Workshop Physics was at once exciting and exhausting. We eliminated the hour-long lectures, and substituted hands-on experience, but old habits are hard to break. Instructors droned on too long at times during "exposi-tions." We often crammed too many activities into a week. Students discovered that learning by inquiry takes time, and that progress can seem agonizingly slow. At the end of the first semester a significant number of students complained that they had done more work in the course than in all their other courses put together. We learned from our experience. By the end of the second semester, we had calmed down enough to evoke more favorable responses from students. In fact one of the sections got the second-highest numerical rating of any of the hundred-odd laboratory science sections taught at Dickinson in the past three years. Students commented most often that they enjoyed being active and acquiring transferable computer skills. The results of tests on mechanics concepts showed statistically significant gains over those of the pre–Workshop Physics students. A full assessment of the educational gains is underway but will not be completed until the third year of the program.

Our experiment will continue, and we hope many introductory physics teachers will join us in this exciting approach to introductory physics education. But even as we expand and refine our program, we look forward to the outcome of the experiments of our colleagues who seek to use computers in different ways or to incorporate twentieth-century paradigms into the fabric of introductory courses. We are all part of the same exhilarating quest to forge a new intellectual canon that renders science education more meaningful and stimulating for students and teachers alike.

1. There is a growing body of physics-education literature. The focus in most of the literature pertaining to concept development is on topics amenable to concrete experience. An excellent introduction to the problems students encounter in developing fundamental concepts in mechanics is contained in a review article by L. C. McDermott, "Research on Conceptual Understanding in Mechanics," Phys. Today 37, 24 (July 1984).
2. G. Allan, "The Canon in Crisis," Liberal Education 72, 89 (1986). This article provides an insightful analysis of the threats to the intellectual canons in various disciplines. George Allan argues that "contemporary intellectuals have increasingly been driven to abandon their belief in objective truth and to seek refuge in relativism." This argument is consistent with Thomas Kuhn's notions about the cultural relativity of the scientific

enterprise. The applications to physics education are obvious. Quantum theory and special relativity have shaken the primacy of classical mechanics in the realms of the very small and the very fast. More recently the emerging field of chaos has threatened our notion of approximate Laplacian determinism even for the motion of large objects moving at ordinary speeds.

3. The Workshop Physics project began officially in October 1986 with a three year grant from the U.S. Department of Education Fund for Improvement of Postsecondary Education.
4. The 1987–88 Workshop Physics staff included Robert Boyle, Priscilla Laws, John Luetzelschwab, Guy Vandegrift, and Neil Wolf from the department of physics and astronomy at Dickinson College and Mary A. H. Brown from Troy State University in Dothan, Alabama.
5. A. Arons, "Achieving Wider Scientific Literacy," Dædalus 112, 91 (1983).
6. R. Karplus, "Educational Aspects of the Structure of Physics," Am. J. Phys. 49, 238 (March 1981).
7. J. Walker, *The Flying Circus of Physics with Answers* (New York: Wiley, 1977); P. Brancazio, *Sport Science* (New York: Simon & Schuster, 1984); K. Laws, *The Physics of Dance* (New York: Schirmer, 1984); C. M. Will, "Newtonian Cosmology," Contribution to the Introductory University Physics Project Conference at Harvey Mudd College, March 1988. Professor Will is from the McDonnell Center for the Space Sciences, Department of Physics, Washington University, St. Louis, MO.
8. In *Alternatives to the Traditional* (San Francisco: Jossey-Bass, 1972), O. Milton describes an experiment in which students in an introductory psychology course who are not exposed to lectures do just as well in the course as those who attend lectures. In *What's the Use of Lectures* (Baltimore: Penguin, 1971), D. A. Bligh presents metaresearch on the educational impact of lectures. The author concludes that lectures are as effective as other methods for the transmission of information, but that most lectures are not as effective as active methods for the promotion of thought. "Peer Perspectives on the Teaching of Science," *Change*, 36 (March/April 1986), S. Tobias describes a study in which a group of experienced college teachers outside of physics helped identify the nature of conceptual difficulties in traditional physics lectures and demonstrations.
9. The literature on peer learning is scant. However, Robert Fullilove from the University of California at Berkeley has used peer interaction almost exclusively in helping minority students succeed in mathematics courses by enhancing their study skills and problem-solving abilities. The program has enjoyed incredible success in the past decade. It has been the observation of the Dickinson Workshop Physics staff that students display more thinking capabilities and are far more articulate with each other when they think no instructor is within earshot. Once a student understands a concept he or she often uses a more comprehensible style of explanation and vocabulary.
10. E. Taylor, "Impulse Mechanics" (Unpublished paper for the Maryland University Project in Physics and Educational Technology, University of Maryland, Department of Physics and Astronomy, College Park, MD 20742, 1987).
11. R. Serway, *Physics for Scientists and Engineers*, 2nd ed. (Philadelphia: Saunders, 1986); D. Halliday and R. Resnick, *Fundamentals of Physics*, 3rd ed. (New York: Wiley, 1988); J. Faughn and R. Serway, *College Physics* (Philadelphia: Saunders, 1986).
12. D. Kolb, *Experiential Learning* (Englewood Cliffs, NJ: Prentice Hall, 1984).
13. W. M. MacDonald, E. F. Redish, and J. M. Wilson, "Freshman Physics with the Microcomputer" (Unpublished paper for the Maryland University Project in Physics and Educational Technology, University of Maryland Department of Physics and Astronomy, College Park, MD 20742, 1988).
14. R. Thornton, "Tools for Scientific Thinking—Microcomputer Based Laboratories for Physics Teaching," Physics Education 22 (1987). Also see R. Thornton's paper, "Tools

for Scientific Thinking: Learning Physics Concepts with Real-Time Laboratory Measurement Tools" in these proceedings.

15. The "Tools for Thinking" project under the direction of Ronald Thornton of the Center for the Teaching of Science and Math at Tufts University is funded by the FIPSE program at the U.S. Department of Education to oversee the use of MBL materials in introductory physics laboratories at a number of other colleges and universities. The "Modeling" project under the direction of Robert Tinker of Technical Education Research Centers was funded by the National Science foundation to develop hardware and software that allow a student to collect real data and develop a mathematical model for the behavior of a system in an interactive fashion.
16. David Trowbridge, of the Center for Educational Computing at Carnegie Mellon University, has developed the software package known as *Graphs and Tracks* for Macintosh, IBM, and Sun computing systems using the cT programming language. Also see D. Trowbridge's paper, "Applying Research Results to the Development of Computer-Assisted Instruction," in these proceedings.
17. Eric Lane's *Standing Waves* software for the Apple II Computer is distributed by Conduit at the University of Iowa. Also see E. Lane's paper, "Animation in Physics Teaching," in these proceedings.
18. B. Cabrera, *Electromagnetism: Physics Simulations II*, available through Kinko's Academic Courseware Exchange in Santa Barbara, CA. Also see B. Cabrera's paper, "Early Experiences with Physics Simulations in the Classroom," in these proceedings.

Tools for Scientific Thinking: Learning Physical Concepts with Real-Time Laboratory Measurement Tools

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Learner-controlled explorations in the physics laboratory with easy-to-use real-time measurement tools give students immediate feedback by presenting data graphically in a manner that they can understand. Using microcomputer-based laboratory (MBL) sensors and software, students can simultaneously measure and graph such physical quantities as position, velocity, acceleration, force, temperature, light intensity, sound pressure, current and potential difference. These MBL tools provide a mechanism for more easily altering physics pedagogy to include methods found to be effective by educational research. The ease of data collection and presentation encourage even badly prepared students to become active participants in a scientific process that often leads them to ask and answer their own questions. The general nature of the tools enables exploration to begin with students' direct experience of the familiar physical world rather than with specialized laboratory equipment. The real-time graphical display of actual physical measurements of dynamic systems directly couples symbolic representation with physical phenomena. Such MBL tools and carefully designed curricula based on educational research have been used to teach physics concepts to a wide range of students in universities and high schools. Data show that students learn basic physical concepts not often learned in lectures when they use MBL tools with carefully designed curricular materials.

Some Problems with Physics Education

There is strong evidence that introductory physics students in the usual college and university lecture courses are not learning concepts necessary to their understanding of the physical world. This paper presents some additional evidence. Traditional science instruction in the United States, refined by decades of work, has been shown to be ineffective in altering student misconceptions and simplistic understandings. Even at the university level, students (even science majors) leave physics courses with fundamental misunderstandings of the world about them essentially intact: their learning of facts about science remains in the classroom and has no effect on their thinking about the larger physical world. The ineffectiveness of these courses is independent of the apparent skill of the teacher, and student performance does not seem to depend on whether students have taken physics courses in secondary school.[1]

One of the reasons that traditional science courses have failed in this respect is that they do not make strong connections between the everyday experiences of the students and the concepts these students learn in the classroom. At the same time these courses do not address the incomplete "understandings" that serve students well within limited domains but do not lead to the general principles underlying deeper scientific understanding. Unless a course is planned carefully to examine simple understandings and to introduce general principles while addressing misconceptions, students' ideas will not change.

Developing Physical Intuition in the Physics Laboratory

Even successful physics students who can solve all of the problems at the end of the chapter generally lack physical intuition—a reliable, accurate response to the physical world based on an understanding of its underlying principles. In fact, physics honors students have been shown to have fundamental conceptual difficulties.[2] In contrast, students who develop physical intuition have a conceptual, qualitative understanding that can be applied outside of the classroom in their everyday interactions with the physical world. Thus it is likely to be fruitful to alter the way we teach science students: we should begin with what students can learn by arranging their interaction with the physical world around them, and then connect that learning to the underlying principles that constitute scientific knowledge.

A well-designed science laboratory can provide the sorts of experiences necessary to correct misconceptions and to develop useful physical intuition. The laboratory is one of the few places where students can truly participate in the processes of science by gaining firsthand knowledge of physical phenomena, constructing the theories necessary to understand the physical world, and formulating their own questions. Altering misconceptions generated by interaction with the physical world requires additional interaction. Recent developments in cognitive science and education substantiate the importance of empirical, heavily phenomenological experiences in learning science skills and concepts.[3] One of the ways Arnold Arons suggests to increase student learning is to provide the means for students to form concepts from concrete experience.[4]

In fact, laboratories are often omitted from or deemphasized in physics courses because the teaching laboratory is thought to be a place not where students learn physics, but a place where they develop laboratory skills of limited academic usefulness. The reality is that many science laboratories do not encourage exploration. They offer "cookbook" instructions that often seem unrelated to physics concepts, and they require time-consuming calculations. Many laboratory instruments are hard to use and unreliable. In addition, the results that emerge after an enormous amount of effort are what one would expect anyway. Because of these things, the traditional physics teaching laboratory is often ignored by faculty and disliked by students. Such laboratories are better omitted from courses because they discourage students. They provide no new information about nature and give an incorrect view of the process of science. Yet science laboratories are not a frill that can be

discarded without consequence. The absence of the direct experience afforded by the laboratory can make science less interesting and less accessible.

Scientists rarely "preach what they practice." Science is exciting to scientists because they are engaged in discovery and in creatively building and testing models to explain the world around them (the practice). In most courses, students "do" no science; they hear lectures about already validated theories (the preaching). Not only do they not have an opportunity to form their own ideas, they rarely get a chance to apply the ideas of others to the world around them.

It is especially important for students in introductory courses to have direct experience with physical phenomena, but inexperienced students are particularly vulnerable to the problems with teaching labs described above. Such students have not developed sophisticated laboratory techniques, honed investigative skills, or become familiar with analytical skills, so it is difficult to construct laboratory experiences where they can successfully ask and answer questions that interest them. The effort to ensure that students with minimal laboratory skills get the "right" answer has led to exercises with overly explicit instructions that direct students through routine steps to confirm known answers to uninteresting questions.

Tools for Scientific Thinking

The Tools for Scientific Thinking project of the Center for Science and Mathematics Teaching at Tufts University is addressing some of the problems outlined above by introducing microcomputer-based laboratory (MBL) tools and curricula for colleges and high schools. Students need powerful, easy-to-use scientific tools to collect and display physical data it in a manner that can be remembered, manipulated, and thought about. Such tools can go a long way toward making teaching laboratories engaging and effective for developing useful scientific intuition. This sort of MBL tool was first developed at the Technical Education Research Centers (TERC),[5] and is now readily available.[6] MBL tools can eliminate the drudgery associated with data collection and display and allow students to concentrate on scientific ideas. MBL tools can be structured to encourage inquiry and thereby avoid "cookbook" laboratories. Because of their ease of use and pedagogical effectiveness, well-designed MBL instruments are especially well suited to the revitalization of science laboratories. Such tools make an understanding of physical phenomena more accessible to naive science learners and expand the investigations that more advanced students can undertake.

MBL instruments give science learners unprecedented power to explore, measure, and learn from the physical world. They do not simulate physical phenomena but change inexpensive computers into instruments for student-directed exploration of the physical world. MBL instruments of the type developed by TERC and Tufts make use of inexpensive microcomputer-connected probes to measure such physical quantities as temperature, position, velocity, acceleration, sound pressure, light, and force. These tools can also measure physiological indicators such as heart rate. Measurements taken by the probes are displayed in digital and graphical form on the computer monitor as the measurement is taken. Data can also be trans-

formed and analyzed, printed, or saved onto disks for later analysis. Carefully developed software makes these laboratory tools easy to use the first time. MBL tools dictate neither what is to be investigated nor the steps of an investigation. Consequently, students feel in control of their own learning. Moreover, these general tools can be used with many different curricula by both physics majors and nonmajors.

As part of the Tools for Scientific Thinking project, we have tested laboratory curricula and MBL tools at varied institutions including California Polytechnic State University, Dickinson College, Massachusetts Institute of Technology, Muskingum College, University of Oregon, Tufts University, and Xavier University. The project is making available a number of microcomputer-based laboratory modules and curricula that emphasize the role of the physics teaching laboratory. The materials are designed to give students the means to build physical intuition (a conceptual, qualitative, usable understanding of the physical world). Such laboratories are accessible to the naive science learner and provide a foundation for the restructuring of science courses for nonmajors as well as majors. The project is funded by the Fund for the Improvement of Postsecondary Education (FIPSE) of the U.S. Department of Education. This project is linked to another FIPSE-funded project, Workshop Physics, which is developing an entire introductory physics course sequence that will replace the traditional physics course with a workshop format designed to enhance student interaction with the physical world.[7]

Learning Kinematics Concepts with MBL Tools and Curricula

Using a motion detector designed by TERC and curricula developed by the Tools for Scientific Thinking project at Tufts, university and high school students have successfully learned kinematics concepts that they did not learn in lectures. The motion detector (hardware and software) is able to measure, display, and record the distance, velocity, and acceleration of any object. The hardware was developed from a sonic transducer used in Polaroid cameras. The motion probe is essentially a SONAR unit that sends out short pulses of high-frequency sound (50 kHz), and then detects and amplifies the echo. A microcomputer is then programmed to measure the time between the transmitted and received pulse and to calculate the position, velocity, acceleration of the object causing the reflection (much as a bat is able to do). Any one of these quantities may be displayed on the computer screen as the data are taken, and all are available after the measurements are completed. The motion detector can accurately detect objects between 0.5 and 6 meters. It detects the closest object in roughly a 15° cone. The motion detectors are connected to Apple II computers.

The kinematics laboratory curriculum was designed using guidelines and beliefs common to curriculum in all of the various subject areas on which the project has been working. A fundamental belief is that physical concepts are best learned in a laboratory setting. The curriculum is heavily based on research and uses a guided- discovery approach that makes use of student predictions, pays

attention to student alternative understandings, supports peer learning, and provides opportunities for students to construct knowledge for themselves. Students use their own motion to learn kinematic concepts.[10]

Student Understanding of Simple Kinematics

Early on we tested students' knowledge of simple concepts in kinematics and classical mechanics so that we could address difficulties in the laboratory. Work by other researchers and our own teaching, had made us aware of the standard alternative understandings and student difficulties.[9] In spite of this knowledge, we were not prepared for the large percentage of university students who had, with even the most basic qualitative concepts. To confirm our findings, we decided to collect results from a larger sample of physics students. Because it is difficult to convince physics professors to give up any course time and because we wanted to make evaluation less subjective, we decided to use short-answer questions. From earlier work with students we evolved a set of short-answer questions that give a reasonable indication of students' basic knowledge about kinematics and its graphical representation. The questions were such that most university physics professors were sure that no more than 10 percent of their students would miss them. Most professors also agreed that students who could not answer questions such as these did not have a basic understanding of kinematics. In fact there was considerable concern that giving such questions was a waste of time and an insult to the intelligence of students.

For this study the sources of the data were college and university physics-teaching laboratories of members of the Tools for Scientific Thinking project. The student population was primarily students enrolled in introductory algebra or calculus-based physics courses. In general students were given two kinematics labs lasting between two and three hours. These labs replaced standard university laboratories. In one case, students were given one laboratory lasting only one hour and 15 minutes. The motion detector connected to an Apple II series computer was used with curricula designed to guide students to explore fundamental motion concepts. Additional characteristics of the curriculum are described above. Students worked in small groups (two to four students). Homework related to the lab was assigned. The labs do not depend explicitly on knowledge gained in lectures or textbooks. The labs covered the position and velocity of moving objects and introduced acceleration. The relationship between force and acceleration was not covered.

The following figures give some of the results of this study. All data presented here, pre- and post-MBL, were taken after students had had the usual kinematics lectures and (in most cases) had done the usual problems. (Other data from smaller student samples seem to show that lectures have no effect on how well students do in the labs. If the labs are done first, class discussions in smaller classes seem to indicate more interest and understanding.) We almost always give the average error rates on a question. Error rates greater than 15 percent on simple conceptual questions such as these are probably cause for altering the curriculum.

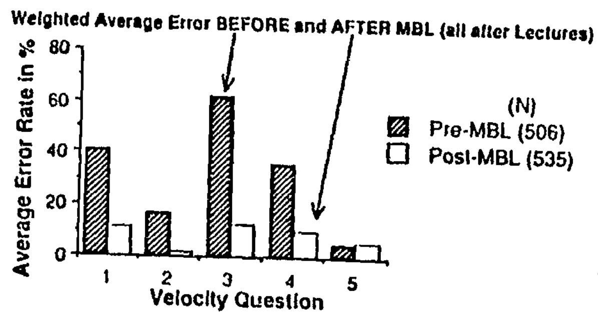

Figure 1. Average error rate on velocity questions after lectures and before and after MBL.

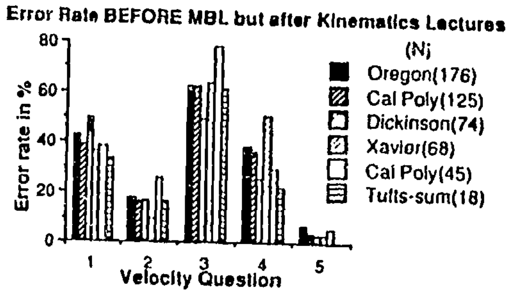

Figure 2. Error rate on velocity questions before MBL but after lecture.

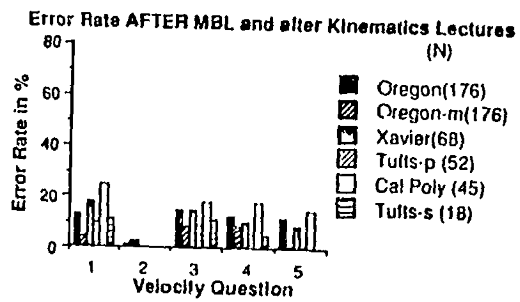

Figure 3. Error rate on velocity questions after MBL and after lecture.

The dark bars in Figure 1 show the weighted average error rate for 506 physics students from five different universities who answered the simple questions shown in Figure 4. The large error rates are especially surprising since these students had recently heard the standard kinematics lectures and worked the problems associated with them. Figure 2 shows the error rates for the questions above for each of the six student populations making up the weighted average. The pattern is remarkably stable across different student populations.

The large error rates associated with questions one and three are not the result of the wrong choice of "sign," which only accounts for a few percent of the answers. The most common error is the choice of the "distance analog" graphs A and B. But the students do not consistently make such a choice, as the different error rates for questions one and three show.

The error rates for the same five questions after one or two MBL motion laboratories are shown in Figure 1 as the white bars. Note that the pre- and post-MBL populations are not identical. Figure 3 shows the six different populations making up the post-MBL results. The pre-MBL sample is 45 percent physics-with-calculus students, while the post-MBL sample is only 28 percent physics-with-calculus students. Calculus students do better than noncalculus students on the pretest but the effect is only about ±10 percent from the average error rate. Post-test results are much closer. In addition, the 52 Tufts students included in the post-MBL sample were in a "Physics for Humanists" science course that did not generally emphasize kinematics. Their MBL lab exposure was only one short lab (about seventy minutes). No pretest was given because most students had not had physics and many could not read graphs.[8] The post-MBL data also include two different post-tests on the Oregon students. One of these tests is delayed (the midterm). Either one can be removed without greatly changing the weighted averages shown in Figure 1. These Oregon data will be examined more closely in what follows.

Smaller sample studies have shown that post-tests given as part of the homework, produce essentially the same results as post-tests given in class for the kind of question above. In general, students do slightly better when the post-test is given in class, which is the reverse of what one might predict. Smaller sample studies also show that students given the same questions for a pretest and post-test do not do better than students given only the post-test.

The Oregon Kinematics Results

Thanks to Professor David Sokoloff, we were able to do more intensive studies with students at the University of Oregon. Figure 5 shows the results on these questions for 172 Oregon students (36 percent were enrolled in a physics-with-calculus course and 64 percent in an algebra-based course. All students had finished kinematics when they took the pre-MBL test. Students were given two labs using the motion detector. Students also received correlated homework questions. The labs primarily concentrated on the distance and velocity of moving objects (includ-

Velocity-time Graphs

An object's motion is restricted to the + distance axis. Pick the best choice(s) for the answer. You may use a graph more than once or not at all.

	Average Error Rates in % (Post Kinematics Lectures) Pre-MBL	Post-MBL
1. Which velocity graph shows an object going away from the origin at a steady velocity? C	41	12
2. Which velocity graph shows an object that is standing still? G	17	2
3. Which velocity graph shows an object moving toward the origin at a steady velocity? D	62	12
4. Which velocity graph shows an object changing direction? F	36	10
5. Which velocity graph shows an object that is steadily increasing its speed? A	5	6
	N=506	N=535

6. Which graphs show objects which are accelerating (+ or -).

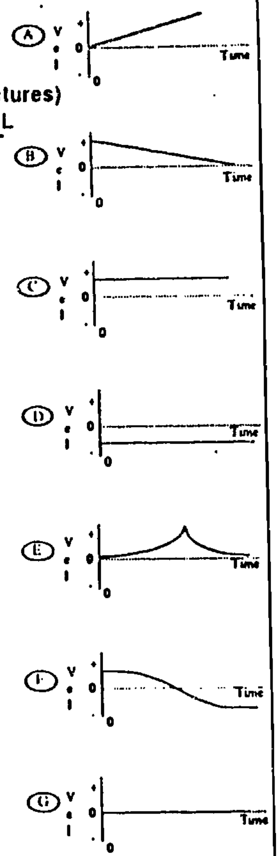

Figure 4. Questions on velocity-versus-time graphs. Questions one through five are the questions referred to in figures 1 through 3. The order of the questions and the graphs was sometimes changed.

ing the students' own bodies). Acceleration was introduced, but not systematically. The post-MBL questions were given as part of the homework, which was graded and returned (answers, however, were not posted).

About three weeks later, the same questions, rearranged, were given as part of the midterm. The results of this delayed-post-test are also shown in Figure 5. The results indicate that the homework helped them to understand kinematics. Is it possible that students have "memorized" the questions after seeing them twice before? Evidence exists that giving a pretest does not help students get better scores on a post-test. Besides, the rearrangement of the questions would prevent strict memo-

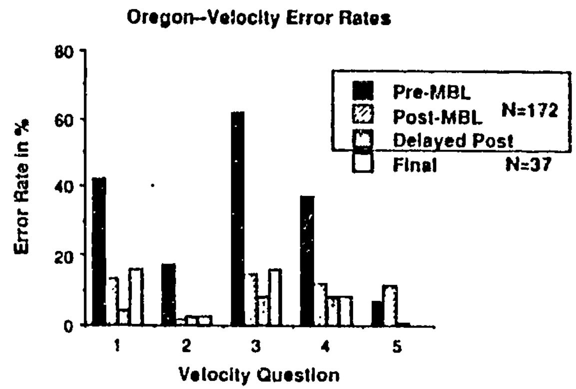

Figure 5. Error rate on velocity question for Oregon class.

rization and the students also did as well on other, different, questions. Therefore, it seems likely that they now understand these simple concepts.

We were able to give the first four questions (again rearranged) to a small sample of 37 noncalculus students as part of their final exam at the end of the term. The results, shown also in Figure 5, seem to indicate that their understanding is retained over a substantial period of time.

We also asked questions on acceleration even though acceleration had only been introduced and not systematically covered in the labs. Some results are shown in Figure 6. The questions are shown in Figure 7.

Figure 8 shows the student error rates for 11 questions on the final exam for 90 students who attended the same lecture session of the algebra-based physics course. The 53 students who did not do the two MBL kinematics laboratories had substantially higher error rates. The lectures were the same for all students. The table below summarizes the average error rates for each category of question.

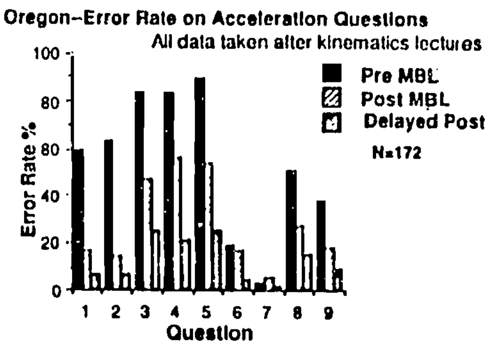

Figure 6. Error rate on acceleration questions.

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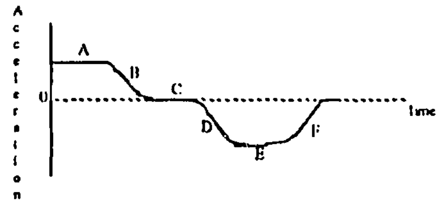
Table 1.

Average Error Rates for Students in the Algebra-Based Physics Course

Topic	Questions	with MBL	without MBL
Velocity	1,3,4	13%	39%
Acceleration	5-9	36%	56%
Force	10, 11	55%	55%

Acceleration-Time Graphs

The graph below is an acceleration-time graph for a car, the motion of which is restricted to the + distance axis. Choose the letter of the section of the graph which could correspond to each of the following motions. Choose the one best answer. If you think that none correspond, write N.



Correct Answer	Error Rates in % Pre-MBL	Post-MBL	Delayed Post
A 1. The car could be speeding up at a steady rate, moving away from the origin	59.	16.	7.
C 2. The car could be moving at a constant speed away from the origin.	63.	14.	7.
E 3. The car could be slowing down at a steady rate, moving away from the origin	84.	47.	25.
C 4. The car could be moving at a constant speed toward the origin	84.	56.	21.
E 5. The car could be speeding up at a steady rate, moving toward the origin	90.	54.	25.

Acceleration

Consider the acceleration in each of the following situations. For each of the following descriptions of the motion of an object, write a "+", "-" or "0" in the space to indicate that the acceleration is positive, negative or zero

- 6. A car is moving in the positive direction and comes to rest	19.	17.	4.
+ 7. A car starts from rest and begins to move in the positive direction	3.	5.	2.
+ 8. A car is moving in the negative direction and comes to rest	51.	27.	15.
- 9. A car starts from rest and begins to move in the negative direction.	38.	18.	10.

Figure 7. Comparison of students who had MBL laboratories to those who did not.

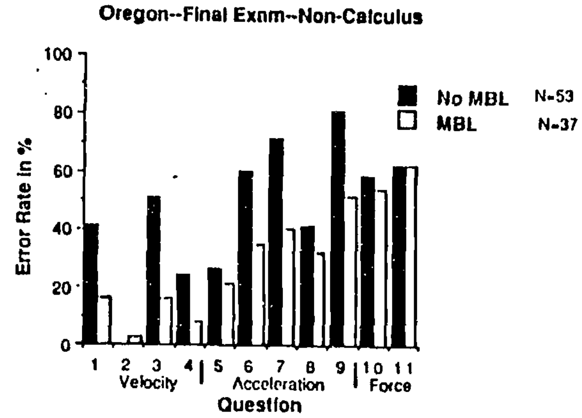


Figure 8. Error rate on each question for Oregon group.

The "with MBL" results are quite consistent with the coverage of the MBL laboratories. The MBL labs covered distance and velocity well. They introduced but did not emphasize acceleration, and they did not cover the relationship between force and acceleration. The velocity questions were selected from the ones described earlier. The error rates of the MBL students increased a few percent compared to the delayed post-test, but retention over the two-month period is very high. The error rates for the no-MBL students are unfortunately consistent with the pre-MBL error rates taken earlier in the course, except that students apparently did learn through the standard treatment to recognize the velocity graph of an object standing still (question 2). Questions 5 through 11 are shown in Figure 9.

Is MBL Software Pedagogically Successful?

There has been considerable discussion about whether computer-based learning offers substantial advantages over other methods, but there has been very little evidence published. Can the MBL software discussed in this paper be considered pedagogically successful? This paper shows evidence of substantial persistent learning of very basic physical concepts by students using a particular set of curricular materials. These same simple physical concepts were not learned by large numbers of students when they listened to good traditional physics lectures, read respected textbooks, and did the traditional algorithmic problems at the end of the chapters. The laboratory curriculum used by these students was made possible (or at least practical) by the use of a microcomputer-based motion tool that used the power of the computer to allow students to see actual measurements of physical phenomena displayed in real time as graphs. The immediate coupling of the graphs to the physical phenomena seems to lead students both to understand graphing as a useful scientific symbol system and also to understand physical concepts from an examination of appropriate phenomena.

Questions 5-11 Given to All Students on the Final Exam

Questions 5-11 refer to the motion of a toy car which is restricted to the + distance axis. Choose the letter of the one correct acceleration vs time graph which could correspond to the motion of the car described in each of the following. If you think that none is correct, answer N. You may use a graph more than once.

E 5. The car moves at a constant speed away from the origin.

B 6. The car speeds up at a steady rate, moving away from the origin.

D 7. The car slows down at a steady rate, moving away from the origin.

E 8. The car moves at a constant speed toward the origin.

D 9. The car speeds up at a steady rate, moving toward the origin.

B 10. A constant force pushes the car away from the origin. (Assume that friction is negligible.)

E 11. The car was given a push, released and now moves away from the origin. Which graph corresponds to the car's acceleration after it was released? (Assume that friction is negligible.)

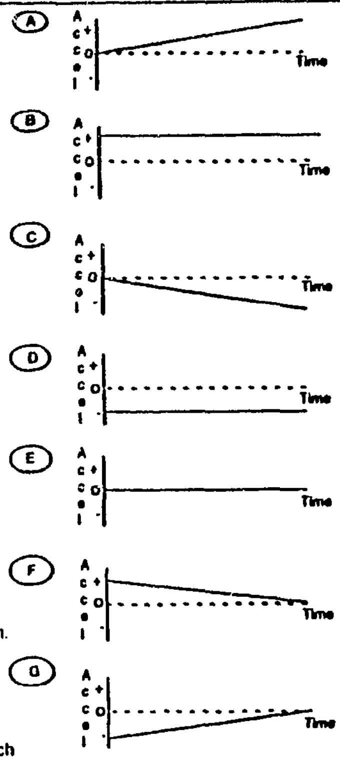


Figure 9. Questions on acceleration versus time. Questions five through eleven were given to all students on the final exam.

What happens when beginning students use MBL tools to do more or less traditional physics experiments? The students are pleased. They may do additional exploration, and they do a better job in general. Preliminary evidence shows that they do not, however, learn fundamental physical concepts unless the means of teaching them are built into the experiments. We can certainly say that the MBL software and hardware tools are pedagogically successful for teaching such physical concepts when used in combination with research-based curriculum materials.

This work was partially funded by the Fund for the Improvement of Postsecondary Education (FIPSE, U.S. Department of Education) under the Tools for Scientific Thinking Project at Tufts University.

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APPENDIX F

This paper has been accepted for publication in the American Journal of Physics

LEARNING MOTION CONCEPTS USING REAL-TIME MICROCOMPUTER-BASED LABORATORY TOOLS[1]

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Microcomputer-based laboratory (MBL) tools have been developed which interface to Apple II and Macintosh computers. Students use these tools to collect physical data which are graphed in real-time and then can be manipulated and analyzed. The MBL tools have made possible discovery-based laboratory curricula which embody results from educational research. These curricula allow students to take an active role in their learning and encourage them to construct physical knowledge from observation of the physical world. The curricula encourage collaborative learning by taking advantage of the fact that MBL tools present data in an immediately understandable graphical form. This paper describes one of the tools--the motion detector (hardware and software)--and the kinematics curriculum. The effectiveness of this curriculum compared to traditional college and university methods for helping students learn basic kinematics concepts has been evaluated by pre- and post-testing and by observation. There is strong evidence for significantly improved learning and retention by students who used the MBL materials, compared to those taught in lecture.

I. INTRODUCTION

Results from research in cognitive science and education substantiate the importance of basing development of scientific concepts and skills on concrete experience.[2,3] The "Tools for Scientific Thinking" project [4,5,6] at the Center for Science and Mathematics Teaching at Tufts University has developed microcomputer-based laboratory (MBL) tools and curricula that can help students make connections between the physical world and the underlying principles which constitute scientific knowledge. These materials, which are intended for use in introductory courses in high school and college, provide a convenient and effective means for collecting and displaying physical data in a form that students can remember, manipulate and think about.

MBL tools of the style described in this paper, were first developed at the Technical Education Research Centers (TERC) [7], and are readily available.[8] They make use of inexpensive probes, connected to an Apple II+, IIe or IIGS computer through an interface box (the "Red Box"), to measure such physical quantities as temperature, position, velocity, acceleration and sound pressure. Additional Apple II MBL tools which are able to measure force and motion simultaneously, current and voltage, and light intensity, have been developed at the Center for Science and Mathematics Teaching at Tufts University. For the Macintosh computer, MBL tools able to measure these physical properties and others (such as ionizing radiation) have been developed at Tufts University and Dickinson College.[9]

Students are not required to know anything about computers to use the MBL tools. Menu-driven, self-explanatory software is friendly, even for first time users, and encourages under-prepared and anxious students. With these tools, students are in control of their learning since they

select the measurements to be made and the way the data are displayed. Data are displayed in digital and graphical form on the computer monitor as the measurements are taken. Students can transform and analyze the data, print graphs or tables, or save data to disks for later analysis. The tools do not simulate physical phenomena, but instead are a means of changing inexpensive computers into instruments for student-directed exploration of the physical world.

The following characteristics of these tools are important to student learning. (1) The tools allow student-directed exploration but free students from most of the time consuming drudgery associated with data collection and display. (2) The data are plotted in graphical form *in real time*, so that students get immediate feedback and see the data in an understandable form. (3) Because data are quickly taken and displayed, students can easily examine the consequences of a large number of changes in experimental conditions during a single laboratory period. The students spend a large portion of their laboratory time observing physical phenomena and interpreting, discussing, and analyzing data. (4) The hardware and software tools are general--independent of the experiments. The variety of probes use the same interface box and the same software format. 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. (5) 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 school to university level are able to use this same set of tools to investigate the physical world.

II. The Motion Detector

The motion detector (hardware and software) is able to measure, display and record the position, velocity, and acceleration of an object. The original motion detector was developed by TERC using a sonic transducer designed for Polaroid cameras. The motion probe (essentially a SONAR unit) transmits short pulses of high-frequency sound (50 kHz), then amplifies and detects the echo (much as a bat is able to do). The computer is programmed to measure the time between the transmitted and received pulses, and to calculate the position, velocity and acceleration of the

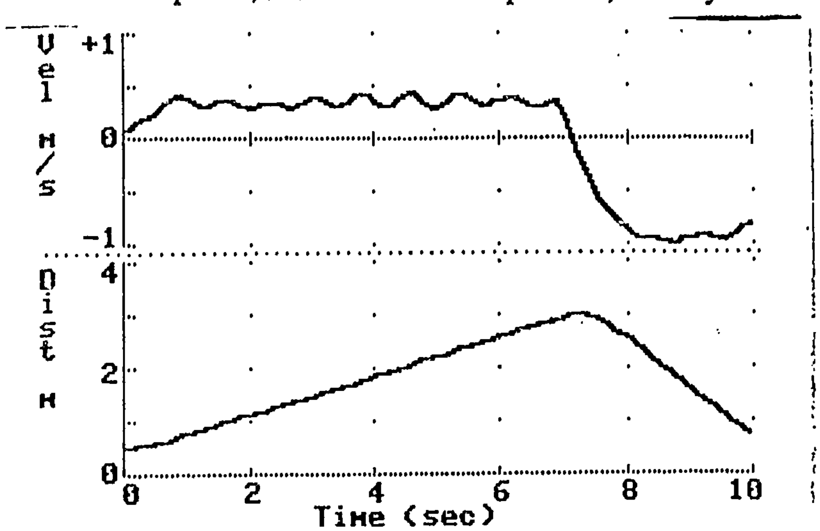


Figure 1 Distance (position) and velocity graphs recorded on an Apple II computer for a student walking away from the motion detector slowly and then moving towards it more quickly. The velocity variations due to the student's steps shows clearly in the velocity graph.

taken, and any one or more are available for display immediately after the measurements are completed. The motion detector can accurately detect objects between 0.5 m and 6 m away. It detects the closest object in a roughly 15° cone.

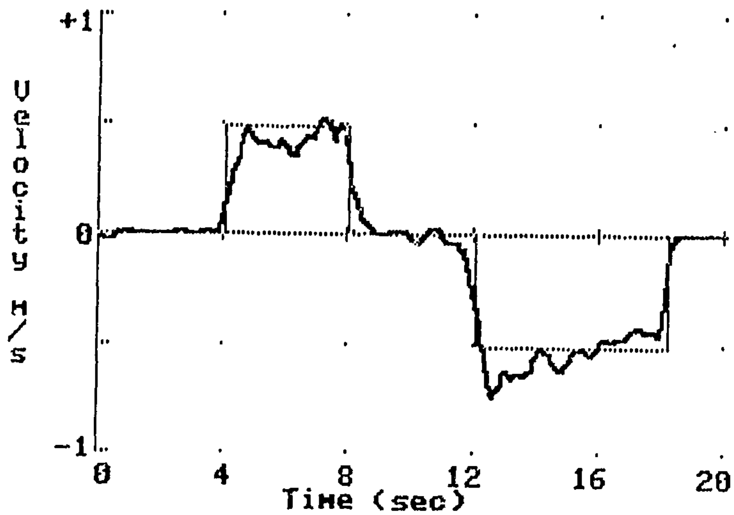


Figure 2 Student's third attempt (solid line) to duplicate with the motion of her body a velocity graph stored in a Apple II computer (dotted line).

Figures 1 and 2 are examples of motion graphs produced by the detector interfaced to an Apple II computer, while Figures 3 and 4 show Macintosh displays. The software enables students to change the scales of the vertical and time axes before or *after* the data are collected. Students who in the past plotted graphs in the corner of a large sheet of graph paper, soon learn to make readable graphs--a general purpose skill, useful in many disciplines. The software allows one set of data to be displayed on the screen while a new set of data are collected and graphed (perhaps after a slight change in experimental conditions). Numerical data are available in tablular form or can be read directly from the graph using the analysis software feature which presents digital values corresponding to the position of a movable cursor on the graph.

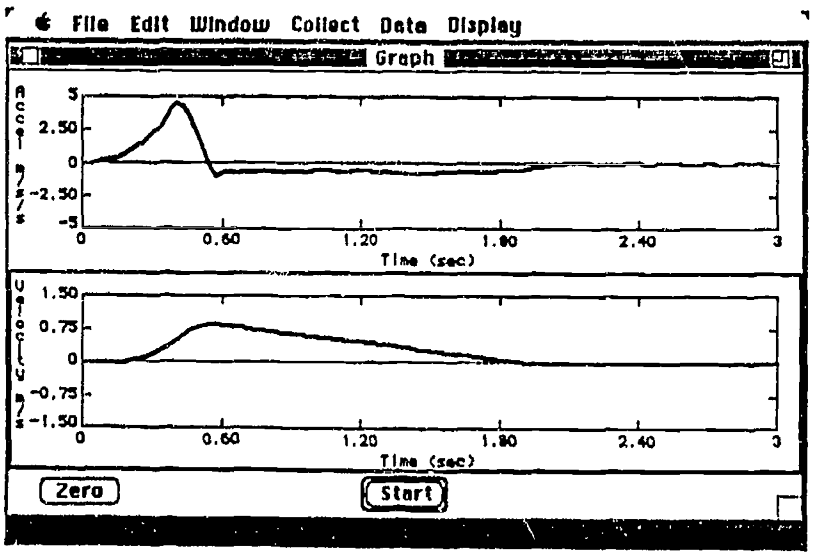


Figure 3 Macintosh screen display of velocity and acceleration graphs for a cart (with friction) given a push away from the motion detector and then released. The surface is horizontal.

One of the most exciting features of the motion detector is its ability to detect and display graphs of the motion of *any* object. 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 simple, common objects such as toy cars and and even the motion of the students themselves. There is no other way of accurately displaying such graphs, certainly not in real time.

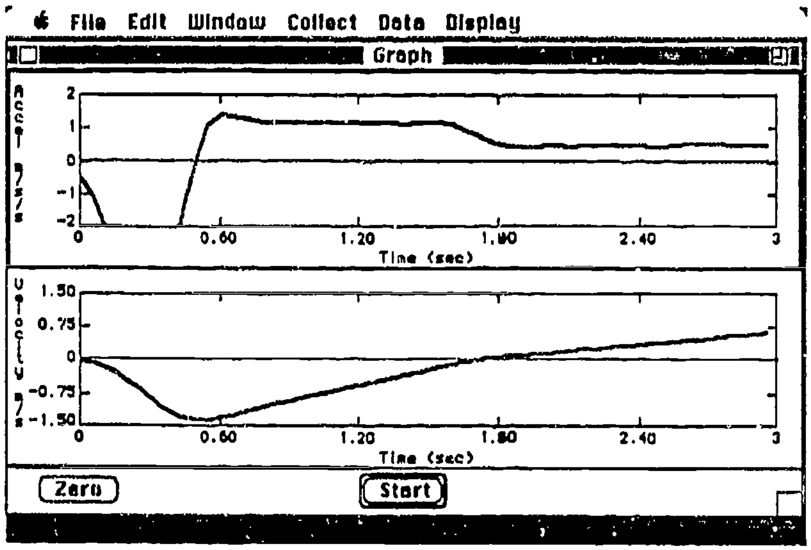


Figure 4 Macintosh screen display of velocity and acceleration graphs for a cart (with friction) rolling up and back down an inclined ramp after a short push. (The motion detector was at the top of the ramp.)

III. The Motion Curriculum

These tools have made possible The Tools for Scientific Thinking curricula for university and secondary-school students developed by the Center for Science and Mathematics Teaching at Tufts University.[10] These discovery-based laboratory curricula allow students to take an active role in their learning and encourage them to construct physical knowledge from actual observation. This paper will discuss only the kinematics curriculum. This curriculum, in common with the others, makes substantial use of the results of educational research.[11,12,13,14] The curriculum uses a guided discovery approach and is intended for student groups of two to four. It supports the peer learning that is possible when data are immediately presented in an understandable form. It also uses predictions to engage the student and provide a vehicle for discussion. It pays attention to student alternative understandings which have been documented in the research literature, and encourages students to construct knowledge for themselves. The introductory parts of the curriculum make substantial use of the students' own body motions to teach kinematic concepts.

The kinematics curriculum is divided into two pieces: *Introduction to Motion*, which covers concepts of position (distance from the motion detector) and constant velocities, and *Introduction to Motion--Changing Motion*, which covers changing velocities and acceleration. Figure 5 shows excerpts from the first page of Investigation 2--the velocity section of *Introduction to Motion* . (Investigation 1 contains a number of exercises with distance graphs.) Students are asked to graph their velocities as they walk quickly and slowly toward and away from the motion detector. They are then asked questions about the graphical representations of *fast, slow, away from* and *toward.* Figure 1 shows typical distance and velocity graphs for moving away from the detector slowly and then moving toward it more quickly. Many students-- including university physics students--are surprised, after viewing inclined distance graphs, to see roughly horizontal lines on the velocity

graphs. These simple and quick exercises are designed to relate velocity graphs to various motions of real objects. Specifically, the exercises clarify the sign convention for velocities and firmly establish the relationship between an object's actual velocity and the displacement of the velocity graph from the time axis. Experience has shown that these simple exercises are necessary even for the majority of university students in calculus-based physics courses.

INTRODUCTION TO MOTION

INVESTIGATION 2: VELOCITY-TIME GRAPHS OF YOUR MOTION

Introduction You have already plotted your distance (position) from the motion probe as a function of time. You can also plot how fast you are moving. How fast you move is your speed or *velocity*. It is the rate of change of distance with respect to time.

Activity 1 **Making Velocity Graphs**

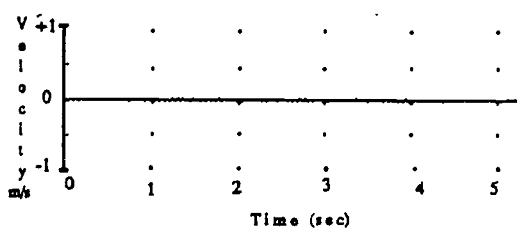
1. Go to the Main Menu. Select **Motion Grapher**, then **Collect**. By selecting **Screens**, you can display **Velocity**. Use **Get Data** when you are ready to begin.

2. Graph your velocity for different walking speeds and directions.

   a. Make a velocity graph by walking *away* from the detector *slowly and steadily*. Try again until you get a graph you're satisfied with.

   You may want to change the velocity scale so that the graph fills more of the screen and is clearer. To do this select **Axes** then **Velocity. Esc** to get back to **Get Data.**

   Sketch your result below (just draw *smooth* patterns; leave out smaller bumps that are mostly due to your steps.)



   b. Make a velocity graph, walking *away* from the detector *medium fast and steadily*. Sketch your graph.

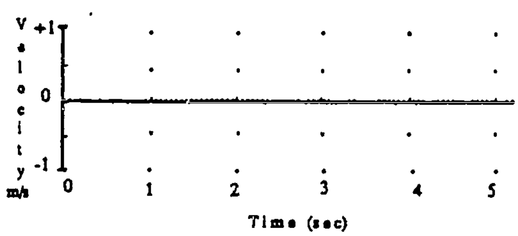


Figure 5 Exerpt from the first page of Investigation 2--the introductory velocity section in the motion curriculum.

After being asked to produce a velocity graph for a more-complicated motion involving walking away, stopping for a few seconds and then walking towards, the students are asked to walk so as to duplicate a velocity graph which appears on the screen. (A similar exercise with a distance graph is included in Investigation 1.) Figure 2 shows the velocity graph to be matched (stored in the alternate display, so that it remains on the screen), and a student's third attempt to duplicate it with her own motion. The velocity graph is deliberately "unrealistic" (it shows several

infinite accelerations) to provoke discussion. In addition, since the motion toward the detector is of longer duration than the motion away, students are forced to observe--when they run into the motion detector on the way back--that a velocity graph does not specify initial position.

INTRODUCTION TO MOTION

Investigation 3: Distance and Velocity Graphs

Introduction You have looked at distance- and velocity-time graphs separately. Now you will see how they are related.

Activity 1 **Predicting Velocity Graphs from Distance Graphs**

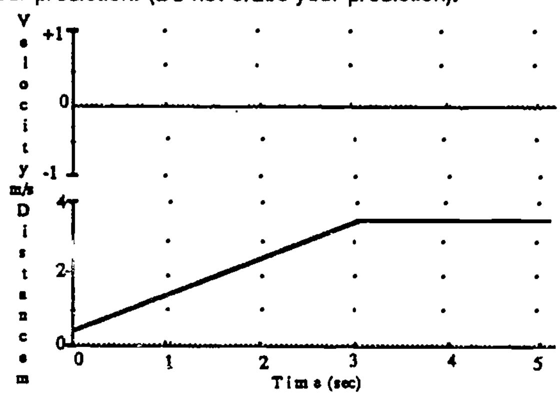
1. Go to the Main Menu. Select **Motion Grapher, Collect, Screens,** then **Split** and **Distance & Velocity.**

2. Predict a velocity graph from a distance graph and check your prediction. Carefully study the distance graph shown below. Using a *dotted line*, sketch your *prediction* of the corresponding velocity-time graph on the velocity axes.

3. Make the graphs. After each person has sketched a prediction, select **Get Data**, then **Distance**, and do your group's best to duplicate the distance graph shown by walking. Walk as smoothly as possible.

   When you have made a good duplicate of the distance graph, sketch your actual graph on the distance axes over the existing graph.

   Press **RETURN** to see the actual velocity graph for your motion. Use a *solid line* to draw the actual velocity graph on the same graph with your prediction. (Do not erase your prediction).



Questions How would the distance graph be different if you moved faster? Slower?

____

____

How would the velocity graph be different if you moved faster? Slower?

____

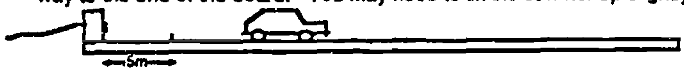
____

Figure 6 Exerpt from Investigation 3. Students are asked to predict the velocity graph corresponding to the given distance (position) graph.

Figure 6 shows excerpts from the first page of Investigation 3, where students are asked to predict the velocity graph for a given distance graph. They then duplicate the distance graph with their body motion, display the corresponding velocity graph and compare the latter to their prediction. Later, they make a more quantitative comparison of the velocity read off the velocity graph to the slope calculated from the distance graph (using the analysis capability of the software to read specific values). They then predict and produce the distance graph corresponding to a given velocity graph.

Activity 2 Graphing Velocity and Acceleration of a Coasting Cart

1. Set up the motion detector at the end of a board. Use a 2-3 meter long board on the floor or a level table top. The detector should be at one end, aimed toward the other end. Use a distance graph to make sure that the detector can "see" the cart all the way to the end of the board. You may need to tilt the detector up slightly.



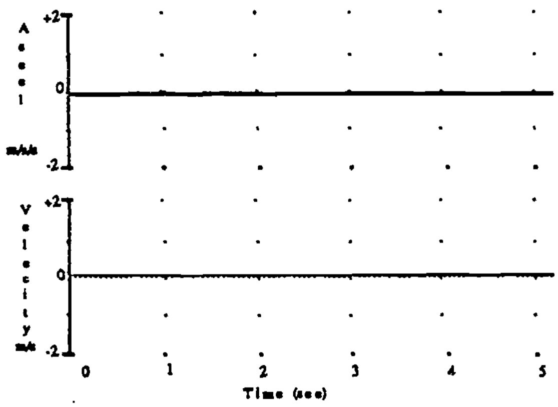
Make a mark on the board .5 meter from the front of the detector, and be sure that the starting point of the cart is always beyond this mark.

Choose a cart with a significant amount of friction, but with wheels that roll smoothly. Use this same cart throughout the rest of this and the next two investigations.

2. Graph the velocity and acceleration of a cart or toy car coasting on the level track. When you begin to hear the clicks from the motion detector, give the cart a gentle push away from the detector and let it coast to a stop near the end of the track. (Be sure that your hand is not between the car and the detector.) You may have to try a few times to get a good run. Don't forget to change the scales if this will make your graphs clearer.

   When you get a good run, move your graph to **Data B.**

3. Neatly sketch your results on the axes below.



Label your graphs with—

"A" at the spot where you started pushing.
"B" at the spot where you stopped pushing.
"C" at the spot where the cart stopped coasting.

Figure 7 Directions for the activity in which a toy car is given a short push away from the motion detector and then released.

Introduction to Motion--Changing Motion, begins with a series of exercises designed to relate the sign of the acceleration to actual changing motions. Students are first asked to walk so as to produce graphs of distance, velocity and acceleration for moving *away from* the detector while *speeding up*. After storing these in the alternate display, they produce graphs walking *toward* the detector quickly at first and then *slowing down*. Then they are asked to predict what the graphs will look like for walking *toward* the detector, *speeding up* and for walking *away, slowing down*. The students then move in the appropriate manner and compare their results to the predictions. Next they graph the motions of a cart, under various conditions. Figure 7 shows an activity where students observe the acceleration and velocity of the cart slowing down and coming to rest from friction. Figure 3 shows the corresponding graphs.

An interesting motion is that of a cart rolling up an inclined ramp, coming to rest and rolling back down. The velocity and acceleration graphs are shown in Figure 4. These graphs illustrate the advantages of tools which allow students to extend their observations beyond specialized cases such as uniform motion on a nearly frictionless air track. We have in fact used a toy car or a dynamics cart modified with an adjustable friction pad on the bottom, so that motion can be examined with different amounts of friction. The different slopes of the velocity graph on the way

up and the way down, combined with the different heights of the acceleration graph are convincing evidence for a frictional force which changes its direction when the cart reverses direction at the top.

The last investigation is a more quantitative one comparing two ways of measuring the accelerations of the cart rolling down a ramp of different inclinations. Accelerations are read directly from the acceleration graphs and compared to accelerations calculated from the slopes of portions of the velocity graphs.

The MBL curriculum has been designed to be incorporated into traditional introductory physics courses found at most colleges and universities, where laboratory sections are often taught by teaching assistants with varying pedagogical skills, and where lecturers pay little attention to the laboratory. In place of the classroom discussions--which under the best of circumstances would be used to consolidate the concepts learned in laboratory--each of these laboratories is accompanied by a homework assignment which the students complete after the laboratory session. They are asked to draw and interpret a number of graphs, similar to and different from the ones they have produced in the laboratory. It is sometimes possible to have these problems discussed in discussion sessions.

IV. How Effective is MBL in Teaching Kinematics?

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 which is rare in a physics laboratory.

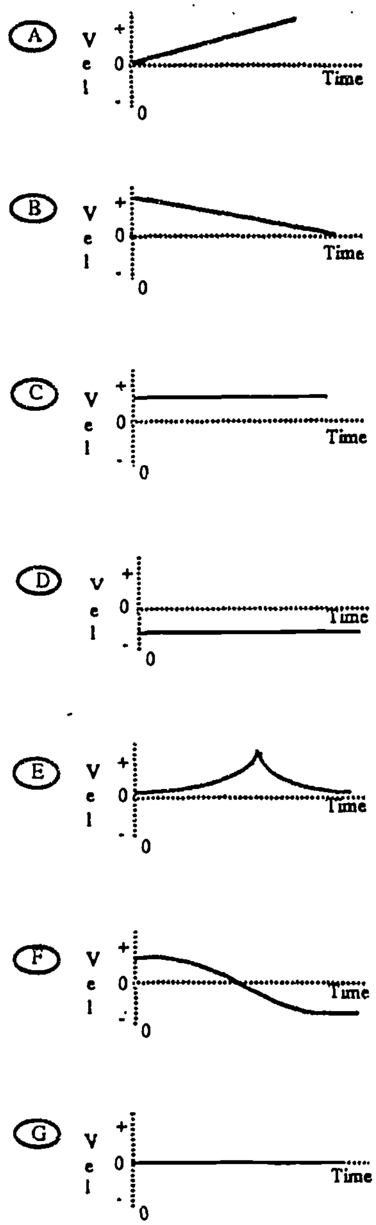
Enthusiasm is one thing, but are the MBL tools and curriculum really effective in teaching kinematics? Over the past three years we have been conducting studies of the effectiveness of the tools and curricula at a number of college and university campuses which are part of the "Tools for Scientific Thinking" project.[15] It has been particularly valuable to collaborate with Priscilla Laws and the Workshop Physics Program[16] at Dickinson College where the tools and some of the curricular pieces have been adapted into a more ideal learning environment. In more usual environments, we have used pre and post-testing and other forms of evaluation to examine the kinematics understandings of more than 1500 college and university physics students. We have also collected data for a large sample of secondary school students which will be discussed in another paper. There is strong evidence for significantly improved learning and retention by students who used the MBL materials, compared to those taught in lecture.[4,5] As examples of these results, we discuss data from Tufts University and the University of Oregon below.

The pre and post-tests that we have used in these studies consist in part of multiple choice questions. From earlier testing of students using free response questions requiring written answers and the drawing of graphs, we have constructed questions which seem to give a reasonable indication of students' basic knowledge of kinematics concepts and of graphical representation. Student results with these questions correlate well with their written answers on these and earlier tests. We find there are almost no random answers. Almost all students pick choices that we can associate with a small number of student models. Many of the multiple choice questions require students to choose the correct graph from a group of graphs. Testing on smaller samples shows that students who can pick the correct graph under these circumstances are almost equally successful at drawing the graph correctly without being presented with choices. Although a more complete understanding of student learning can be gained by an open-ended questioning process, we decided to use short answer questions in order to gather sufficient data at many different institutions to counter the common response that "my students do not have these difficulties you describe." The difficulties in convincing physics professors to give up course time

for testing, our desire to make evaluation less subjective, and the effort involved in analyzing large samples moved us to use short answer questions for these studies.

Velocity-Time Graphs

An object can move in either direction along the + distance axis. Choose the correct velocity-time graph(s) for each of the following questions. You may use a graph more than once or not at all. If you think that none is correct, answer J.



_C_ 1. Which velocity graph shows the object moving away from the origin at a steady (constant) velocity? (A)

_G_ 2. Which velocity graph shows the object standing still? (C)

_D_ 3. Which velocity graph shows the object moving toward the origin at a steady (constant) velocity? (B)

_F_ 4. Which velocity graph shows the object reversing direction? (E)

_A_ 5. Which velocity graph shows the object increasing its speed at a steady (constant) rate? (D)

Choose three velocity graphs which show the object accelerating. (Positive or negative acceleration.)

_A_ 6. _B_ 7. _E_ 8.

or F

Figure 8 Some of the multiple choice velocity questions asked on the kinematics pre and post-tests. Questions 1 through 5 are the velocity questions referred to in the following figures. The order of the questions and the graphs were sometimes changed. The most common wrong answer is shown in parenthesis

In fall, 1987, all of the students in the Introductory Physics Laboratory course (Ph 204) at the University of Oregon were pre and post-tested on their knowledge of kinematics. This is a standard, introductory laboratory which is offered as a separate course to accompany both the non-calculus and calculus-based General Physics lecture courses. (About 64% of the students were in the non-calculus lecture--Ph 201, while the other 36% were in the calculus-based lecture--Ph 211.)

The pre-test was given in the weekly lecture which accompanies the laboratory sections. At the time of the pre-test, the non-calculus lecture class had heard all of the lectures on one-dimensional kinematics and dynamics, and had been assigned the corresponding text readings and problems. The calculus lecture class also had completed one-dimensional kinematics and a preliminary consideration of dynamics. The pre-test was given before the students did the two MBL kinematics laboratories.

Figure 8 shows a few of the simple, multiple choice velocity questions given on the pre-test, and Figure 9 shows the results. It was surprising to observe error rates as high as 40-60% on these simple velocity questions *after kinematics had been covered in lecture.* Most physics professors had predicted that fewer than 10% of their students would miss these questions and felt that students who were unable to answer such simple questions understood very little kinematics. The large error rates on questions 1 and 3 (43% and 62% respectively) are not simply the result of the wrong choice of sign. The most common error is the choice of the "distance analogs," graphs A and B. This is consistent with previous studies,[12,14] in which students confused position and velocity graphs. The different error rates on these two questions show that students have significantly more difficulty interpreting negative velocities. (This conclusion is born out by the results of additional testing.) Neither the results of this pre-test, nor the correct answers were shared with the students. It should be noted that most students did not miss the questions because they were simply unable to read graphs. More than 90% could answer questions involving distance graphs correctly.

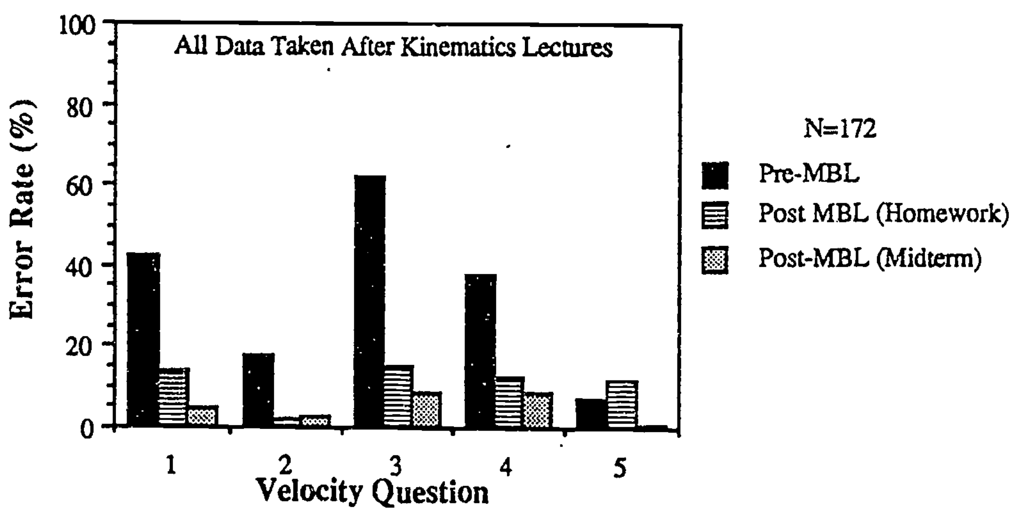


Figure 9 Comparison of the velocity question error rates before and after MBL for introductory physics laboratory students (in non-calculus and calculus-based lectures) at the University of Oregon, Fall, 1987. The pre-MBL test was given after lecture instruction and problem assignments in kinematics. The same questions were given as part of the homework for the two MBL laboratories and then again three weeks later on a midterm examination.

Over the next two weeks, the students completed the two MBL kinematics laboratories described above in place of standard experiments. As part of the homework turned in after completion of the first laboratory, the students were asked the same velocity questions. The tabulated error rates for this homework also are shown in Figure 9. The improvements are dramatic. The homework was graded and returned, but the correct answers were not posted. Three weeks after completing the MBL experiments, the students were given a laboratory midterm

examination, administered in the laboratory lecture. The same velocity questions, rearranged, appeared on the midterm. The results on the midterm are also shown in Figure 9.

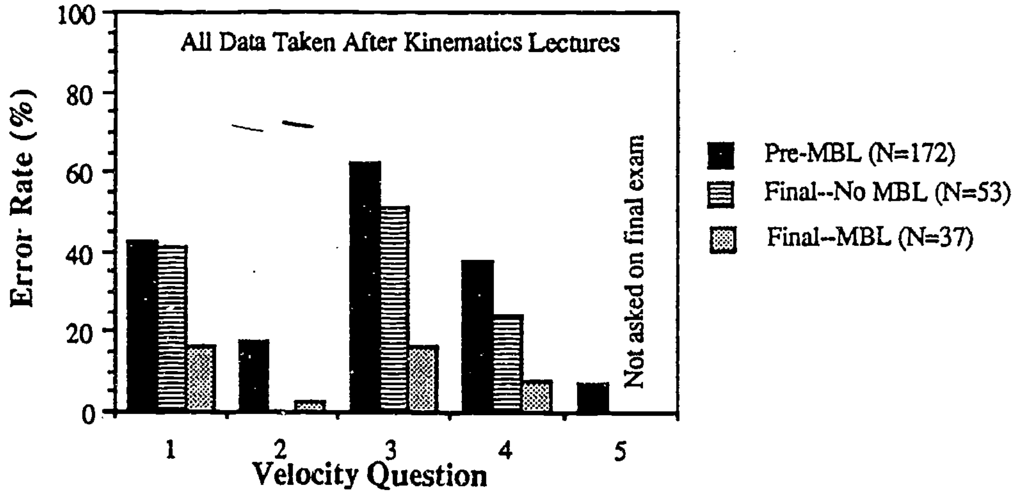


Figure 10 Comparison of the velocity question error rates on the final examination for MBL laboratory and non-laboratory students (all in the non-calculus-based lecture) at the University of Oregon, Fall, 1987.

Velocity questions 1-4 were included on the final examination for one of the non-calculus lecture sections in order to test the retention of students who seemed to understand velocity concepts and to compare their understanding to students who did not take the MBL laboratory. The order of the questions was again rearranged to minimize any possible effects of memorization. This examination was given 7 weeks after the completion of the motion experiments. Of the 90 students who took this examination, 37 were also enrolled in the laboratory (and were included in the laboratory pre-test sample) while the other 53 were enrolled only in the lecture (and therefore did not take the pre-test). Figure 10 compares the error rates on the laboratory pre-test with the error rates for each of these two groups on the final exam. The MBL lab group retained the significant improvement seen on the midterm, while the lecture only group showed mastery on only one of the questions--question 2, identifying the velocity graph of an object standing still.

In the fall of 1988, students in the introductory physics classes at Tufts University were given the same velocity questions as part of fifty-question pre and post-tests. (At Tufts, the laboratory and lecture courses are tied together, but, as at Oregon, the students in both the non-calculus lecture--Ph 1, and the calculus-based lecture--Ph 11, do the same experiments.) As at Oregon, the pre-test was given *after* kinematics had been covered in lecture, but immediately before the first MBL motion laboratory. The post-test was given a few weeks after the two motion laboratories had been completed. Both the questions and the choices were shuffled on the post-test. The students turned in homework assignments which did not contain these questions. The results for students in the non-calculus lecture are shown in Figure 11, while those for the calculus students are shown in Figure 12. The two sets of results are remarkably similar.

Also in the fall of 1988 three of the same velocity questions (the more difficult ones) were included on tests given to students in the non-calculus lecture sections at the University of Oregon. The post-test was given to all three sections, but it only was possible to give the pre-test to two of the lecture sections. Since the populations of these lecture sections were random (the only selection criterion was time of day) the pre-tests should have been similar for all three. The results showed no significant differences between the two sections which were pre-tested. Of the total of 294 students in these lectures, 124 also were enrolled in the laboratory. Thus we were able to

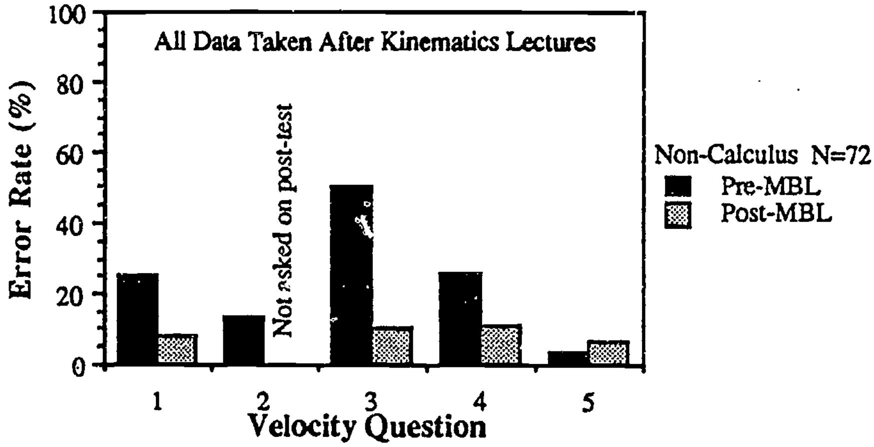


Figure 11 Results for non-calculus-based introductory physics students at Tufts University, Fall, 1988--comparison of student error rates on a few velocity questions given on the pre-test (Pre-MBL) and post-test (Post-MBL). The pre-MBL test was given after all lecture instruction and problem assignments in kinematics. The post-test was given a few weeks after two MBL laboratories.

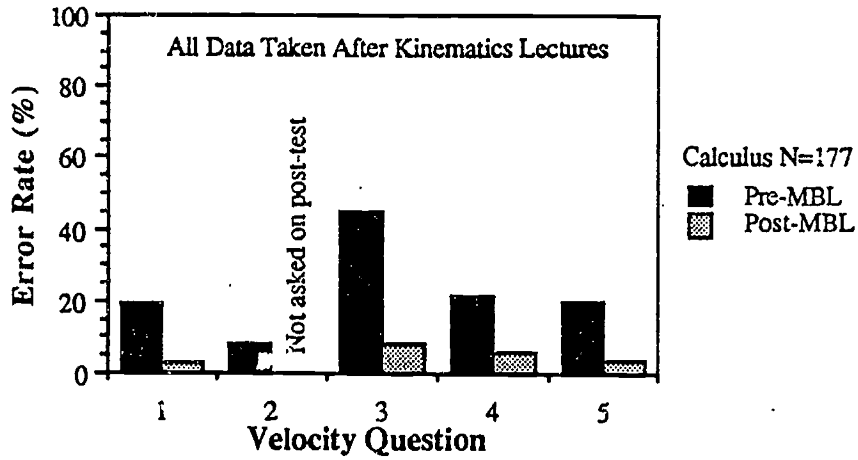


Figure 12 Same as Figure 11 but for calculus-based introductory physics students at Tufts University, Fall, 1988.

compare the learning of students who listened to lectures and did problems to the learning of those who also participated in MBL laboratories. All of the lecturers were aware of the testing, and all made a special effort to teach kinematics graphing and concepts in their lectures. For these students the pre-test was given in lecture *before* any lectures on kinematics (unlike 1987) and before the MBL laboratories. The post-test was given either as a quiz or as part of a midterm examination in the week after the two motion laboratories had been completed. The homework did not contain the questions used in the tests.

Figure 13 shows the results. Notice that the results of the pre-test in Figure 13 given before lecture are similar to those in 1987 (Figure 9), when the pre-test was given *after* all lectures on kinematics. Also, the post-test error rates for students who had only lectures are very similar to their pre-test error rates. These results corroborate previous work involving different types of

velocity questions and the conclusions of other studies that students gain little from their lecture experience in their understanding of velocity concepts.[11,17] On the other hand, the lower post-test error rates for students who completed the two MBL laboratories show significantly improved kinematics understanding.

The results for one of the three lecture sections--a special, small sectio where all the students were also enrolled in the laboratory--are shown separately and labeled as "special." The pre, post and final examination results for the special section also are shown in Figure 13. As noted above, the students were not specially selected for this section. The students have error rates on the pre-test that are very similar to those of the combined lecture sections. However, the special section performed much better on the post-test. We attribute this result to the efforts of the special section instructor who consciously connected his lectures to the knowledge students discovered using the MBL curriculum. (High school students show even lower post-MBL error rates under conditions where they are able to discuss their MBL laboratory results and resolve disagreements and difficulties under teacher guidance.) As was done the previous year, the velocity questions with higher initial error rates (1, 3 and 4) were included on the final examination to check retention. The final was given about 8 weeks after the two MBL kinematics laboratories were completed. The error rates show that most of the students retained their knowledge through the end of the term.

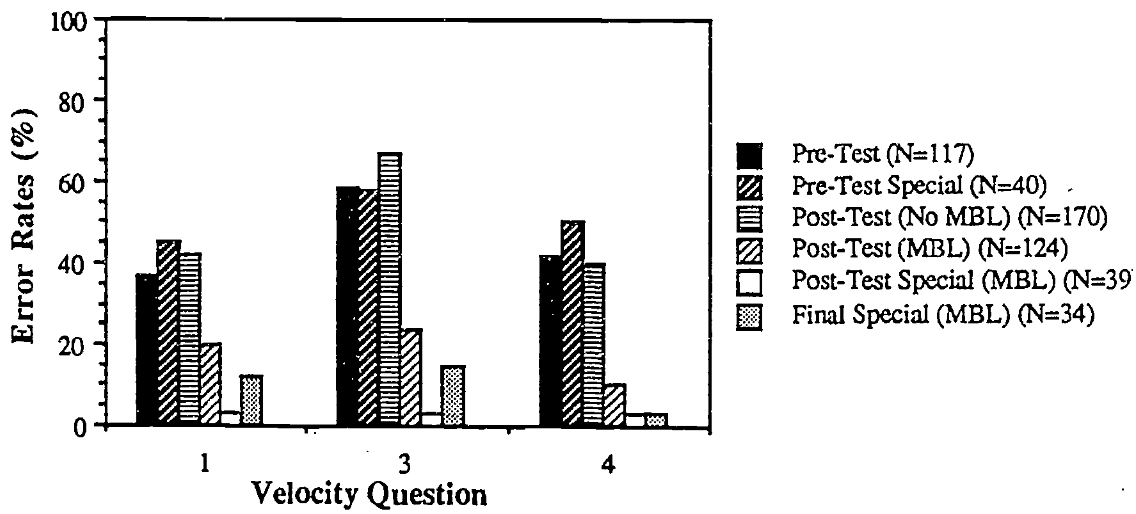


Figure 13 Results for introductory physics lecture students (non-calculus) at the University of Oregon, Fall, 1988--comparison of student error rates on a few velocity questions given on the pre-test, post-test and final examination for those who took the MBL laboratory (MBL) and those who did not (No MBL). The "Special" group is a small lecture section where all students took the MBL laboratory (described further in the text).

The results for one of the three lecture sections--a special, small section, where all the students were also enrolled in the laboratory--are shown separately and labeled as "special." The pre, post and final examination results for the special section also are shown in Figure 13. As noted above, the students were not specially selected for this section. The students have error rates on the pre-test that are very similar to those of the combined lecture sections. However, the special section performed much better on the post-test. We attribute this result to the efforts of the special section instructor who consciously connected his lectures to the knowledge students discovered using the MBL curriculum. (High school students show even lower post-MBL error rates under conditions where they are able to discuss their MBL laboratory results and resolve disagreements

and difficulties under teacher guidance.) As was done the previous year, the velocity questions with higher initial error rates (1, 3 and 4) were included on the final examination to check retention. The final was given about 8 weeks after the two MBL kinematics laboratories were completed. The error rates show that most of the students retained their knowledge through the end of the term.

Acceleration questions were also included on the tests given to the same Tufts and Oregon students in 1988. Figure 14 shows some of the acceleration questions. Figure 15 shows the percentage of Tufts students in calculus and non-calculus based physics courses who missed these questions. The pre-test (given after lectures but before MBL) shows much higher error rates on the acceleration questions than on the velocity questions. The highest error rate is 93% on the question about speeding up *toward the origin*. These results are consistent with other studies [13,18] that show acceleration is considerably more difficult for students. Tufts students do not

A toy car can move in either diretion along the + distance axis. Choose the letter of the acceleration-time graph which could correspond to the motion of the car described in each of the following.

You may use a graph more than once or not at all. If you think that none is correct, answer J.

__27. The car moves away from the origin at a constant velocity.

__28. The car moves away from the origin speeding up at a steady rate.

__29. The car moves away from the origin slowing down at a steady rate.

__30. The car moves toward the origin at a constant velocity.

__31. The car moves toward the origin, speeding up at a steady rate.

__32. A constant force pushes the car away from the origin. (Assume that friction is negligible.)

__33. The car was given a push, released and now moves away from the origin Which graph corresponds to the car's acceleration after it was released? (Assume that friction is negligible.)

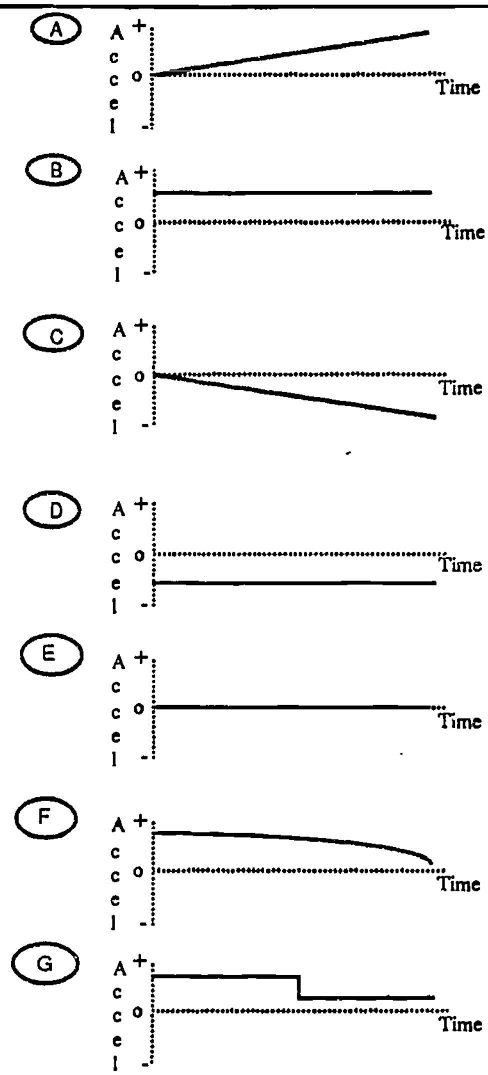


Figure 14 Some of the multiple choice acceleration questions asked on the kinematics pre and post-tests. The question numbers correspond to those used in the following figures.

understand acceleration as well as they understand velocity after the MBL laboratories, but the improvement is still substantial. The Oregon results are shown in Figure 16. The different student

groups are the same as those in Figure 13. Again the results show that the students who only listened to lectures and did problems show no improvement on these concepts, while the students who worked with the MBL curriculum showed considerable improvement. Again this learning was retained by most students to the end of the semester. (Much better understandings of acceleration have been achieved by high school students using a very similar curriculum when the work done by the students was also discussed in the classroom.)

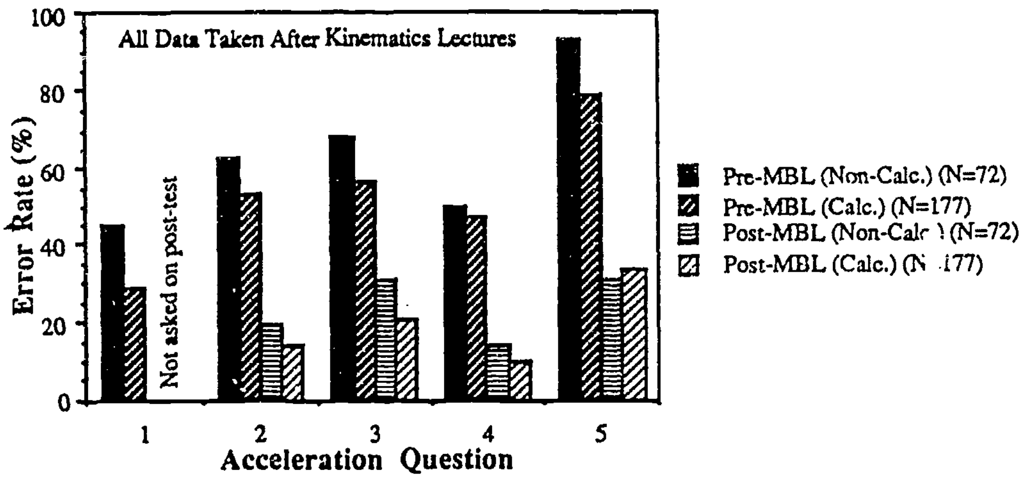


Figure 15 Results for introductory physics students in calculus (Calc.) and non-calculus-based lectures (Non-Calc.) at Tufts University, Fall, 1988--comparison of student error rates on a few acceleration questions before MBL but after kinematics lectures (Pre-MBL) and after MBL (Post-MBL).

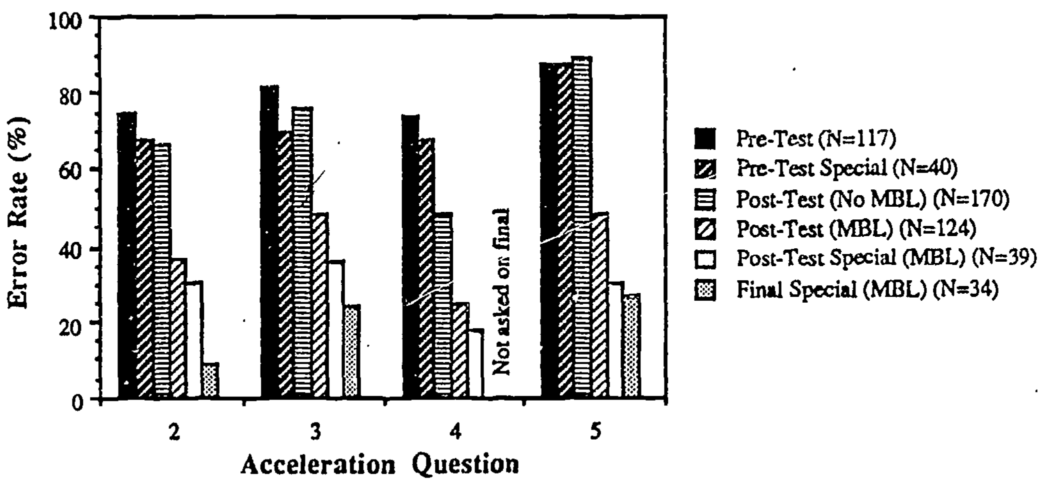


Figure 16 Results for introductory physics lecture students (non-calculus) at the University of Oregon, Fall, 1988--comparison of student error rates on a few acceleration questions given on the pre-test, post-test and final examination for those who took the MBL laboratory (MBL) and those who did not (No MBL). The "Special" group is a small lecture section where all students took the MBL laboratory (described further in the text).

V. Conclusions

The MBL tools give students the opportunity to *do real science* in the introductory physics course. Thus students can experience the excitement of the process of science--the creative building and testing of models to explain the world around them. These tools give the science learner unprecedented power to explore, measure and learn from the physical world. Because of their ease of use and pedagogical effectiveness, they make an understanding of physical phenomena more accessible to the naive science learner[19] and expand the investigations that more advanced students can undertake.

The tools, however, are not enough. Preliminary evidence shows that while the use of the MBL tools to do traditional physics experiments may increase the students' interest, such activites *do not* necessarily improve student understanding of fundamental physics concepts of the type discussed in this paper. These gains in learning physics concepts appear to be produced by the combination of the tools *and* the appropriate curricular materials. In general students improve their understanding of the physical concepts when they are guided by a curriculum to examine appropriate phenomena.

This paper has presented evidence for substantial, persistent learning of very basic physical concepts by students using MBL tools and curriculum. We believe that the following five characteristics of the MBL learning environment--made possible by the tools, the curriculum, and the social and physical setting--are primarily responsible for the learning gains. Note that most of the characteristics of this learning environment bear more resemblance to the scientific workplace than to the usual educational environment.

1) **Students focus on the physical world.** Students learn concepts by investigating the physical world rather than only manipulating symbols or discussing abstractions as is common in traditional courses. However, in this learning environment, actions in the physical world are directly linked to useful abstractions. For example, students who see the motion of their own bodies and of other objects displayed graphically in real time learn kinematics effectively.

2) **Immediate feedback is available.** The immediate feedback helps to make the abstract more concrete. The immediate coupling of the graphs to the physical phenomena seems to lead the students not only to understand graphing as a useful scientific symbol system, but also aids understanding of physical concepts when students are guided to examine appropriate phenomena. These observations are consistent with previous studies on a small number of students which suggested that even a short delay in the display of data in graphical form can reduce learning.[20]

3) **Collaboration is encouraged.** Immediate feedback supports collaborative learning and collaborative work provides immediate feedback. Because data are presented in an understandable way, students can discuss the validity, the meaning and the implications of the data with their peers. Learning is also enhanced by encouraging students to express their predictions and to discuss unexpected results with their peers. This process appears to be a powerful one in learning about the students' alternative representations, and in making them aware of them. The process of working collaboratively is closer to the way scientists actually work.

4) **Powerful tools reduce unnecessary drudgery.** Instead of the time-consuming drudgery usually associated with data collection and display in the physics laboratory, student time is spent observing physical phenomena and analyzing and interpreting abstract representations of these phenomena (graphs). Students are able to concentrate more on discovering and understanding scientific concepts, and critical thinking skills are more easily developed. Hypothesis development and verification is encouraged by the ease and rapidity of repeating observations with changed experimental conditions. Powerful tools allow students to focus on authentic tasks in ways characteristic of scientists in the workplace. This is not commonly the case in school environments.

5) **Students understand the specific and familiar before moving to the more general and abstract.** The environment guides students to understand a specific, familiar (but often more complex) phenomenon before moving to the consideration of more general and abstract examples. Most students seem better able to understand motion when first considering, for example, their own motion (as complex as it is) as a reference point and then moving on to more idealized, less familar (and less complex) motions with more general applicability such as frictionless motion or simple harmonic oscillation. Although it is difficult to abstract simple laws of physics from a complex, real process, grounding student understanding in the specific and familar seems to make the abstract concepts more learnable. Moving from the specific to the general when investigating new concepts may also be more characteristic of the scientific workplace than the usual teaching and learning environment.

The effectiveness of the MBL tools and curriculum in teaching kinematics has encouraged the development of tools and curriculum to teach dynamics. A force probe which makes use of a Hall effect transducer has been developed at Tufts.[9] We have developed new software for Apple II and Macintosh computers which uses the force and motion probes to measure simultaneously force and position, velocity, and acceleration. Figure 17 shows graphs of the motion of a weight oscillating on a spring. Preliminary results show that these tools, when used with a guided, discovery-based curriculum produce substantial gains in student understanding of concepts associated with Newton's laws of motion.

Microcomputer-based laboratory tools and curriculum have the potential to help students develop a solid conceptual basis for understanding the world around them. Through the use of these materials, students' interactions with the physical world can be connected to the underlying principles which constitute scientific knowledge, thereby helping them to develop a conceptual, qualitative understanding which can be applied both inside and outside of the classroom.

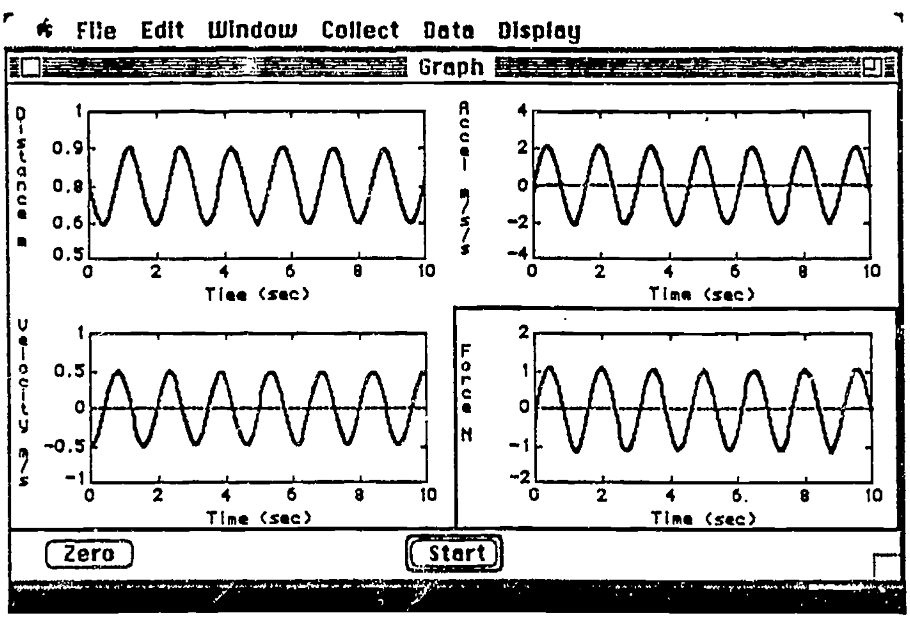


Figure 17 Macintosh screen display of the motion of a weight on a spring (simple harmonic oscillation) measured simultaneously by MBL force and motion detectors. Any of these plots can be graphed as the data are measured.

Acknowledgements

We are grateful to the physics lecture and laboratory instructors at the University of Oregon--Stanley Micklavzina, Jack Overley, Kwangjai Park and Nilendra Deshpande, and at Tufts University--Gary Goldstein, Howard Sample, Katherine McCarthy and especially Denise Robichaud, for their assistance in collecting pre and post-test data. We also thank the other members of the Tools for Scientific Thinking Project, Robert Teese, Priscilla Laws and Stephen Yerian for their suggestions in writing the motion curriculum, and for testing it with their classes. Finally we thank Jayashree Ramadas for her careful data analysis, and Lillian McDermott, Elena Sassi and Edwin Taylor for reviewing the paper and offering many constructive suggestions.

1 This work was supported in part by the Fund for Improvement of Post-secondary Education (FIPSE) of the U.S. Department of Education under the "Tools for Scientific Thinking" project at Tufts University.

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7 Technical Education Research Centers, 1696 Massachusetts Avenue, Cambridge, MA 02138.

8 The HRM Motion, Heat and Temperature and Sound microcomputer-based laboratory tools are available from Queue, Inc., 338 Commerce Drive, Fairfield, CT 06430.

9 For more information write to Ronald Thornton, Center for Science and Mathematics Teaching, Lincoln-Filene Building, Tufts University, Medford, MA 02155 and Prof. Priscilla Laws, Department of Physics and Astronomy, Dickinson College, Carlisle, PA 17013. These materials are available through Vernier Software, 2920 S.W. 89th Street, Portland, OR 97225.

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APPENDIX G:
Dissemination of Workshop Physics and Tools for Scientific Thinking Concepts

KEY TO DEGREE OF IMPLEMENTATION

Requested Information	RI
Purchased Materials / Partial Classroom Implementation	P
Full Implementation	F
Visited Dickinson College to Observe Workshop Physics	V

School or Individual	City State Zip	Degree of Implementation
AAPT Executive Office	College Park, MD 20740	P
Afdeling Didaktiische Fysika	B-3000 Leuven (Belgium)	RI
American Institute of Physics	New York, NY 10017	P
Arizona State University	Tempe, AZ 85287	RI
Austin College	Sherman, TX 75090	RI
Barnard College	New York, NY 10027	P
Boise State University	Boise, ID 83725	RI, V
Bronx		RI
California State University	Hayward, CA 94542-9988	RI
Carmel High School	Carmel, IN 46032	RI
Carnegie Mellon University	Pittsburgh, PA 15213	RI
College of Misericordia	Dallas, PA 18612	RI
Community Education Center	Portage, MI 49002	RI
Crescent Valley High School	Corvallis, OR 97330-9735	RI
Denison University	Granville, OH 43023	RI
Department of National Defense	Ottawa, Canada	RI
Drake University	Des Moines, IA 50311	RI
Drew University	Madison, NJ 07940	RI
Eastern Illinois University	Charleston, IL 61920	RI
Eastern Michigan University	Ypsilanti, MI 48197	RI
Elmhurst College	Elmhurst, IL 60126	RI
Fordham University	Bronx, NY 10458	RI
Framingham School District	Framingham, MA	RI
Freedom High School	Bethlehem, PA 18017	RI
Furman University	Greenville, SC 29613	RI
George Gittins	Eugene, OR 97401	RI
Gettysburg High School	Gettysburg, PA	F, V
Goddard Space Flight Center	Greenbelt, MD 20771	RI
Guilford College	Greensboro, NC 27410	RI

School or Individual	City State Zip	Degree of Implementation
Harrisburg Area Community College	Harrisburg, PA 17110	RI, V
Harry Burridge	Corvallis, OR 97330	RI
Harvey Mudd College	Claremont, CA 91711	RI
Hastings College	Hastings, NB 68901	P
Horton Watkins High School	Ladue, MO 63124	P
Imperial College of Science & Technology	London SW7 2BP	RI
Jo Anne Hogfoss	Eugene, OR 97401	RI
John Rogers	Omaha, NE 68134	RI
Johnson C. Smith University	Charlotte, NC 28216	F, V
Jonathan Keohane	Eugene, OR 97401	RI
King's College, University of Loudon	Loudon SW10 OUA United Kingdom	RI
Lawrence University	Appleton, WI 54911	RI
Lowell Herr	Portland, OR 97219	RI
Lynchburg College		RI, V
Madison Central High School	Old Bridge, NJ 08857	RI
Marietta College	Marietta, OH 45750	RI
Massachusetts Institute of Technology	Cambridge, MA 02139	RI, V, P
Memorial University of Newfoundland	St. Johns, NF, Canada AIB 3X7	P
Mento College	Atherton, CA 94025	RI
Mercer University	Macon, GA 31207	RI
Michael Hodgert	Eugene, OR 97404	RI
Mississippi State University	Mississippi State, MS 39762	RI
Montclair State College	Upper Montclair, NJ 07043	RI
Mount Vernon College	Washington, DC 20007	RI
National Science Foundation	Washington, DC 20550	RI
New Mexico State University	Las Cruces, NM 88003	P
Norman Chonacky	Clinton, NY 13323	RI
North Carolina State University	Raleigh, NC 27695-8202	RI
Ohio State University	Columbus, OH 43210	F
Paul Haley	Eugene, OR 97405	RI
Pierce College	Tacoma, WA 98498	RI
Pioneer High School	San Jose, CA 95118	RI
Pomona College	Claremont, CA 91711-6348	RI
Porterville College	Porterville, CA 93257	RI
Regional College of Education	AJMER-305004, India	RI
Rider College	Lawrenceville, NJ 08648	RI
Roanoke Valley Governors' School	Roanoke, VA 24018	RI
Robert Tinnell	Salem, OR 97302	RI
Rose-Hulman Institute of Technology	Terre Haute, IN 47803	RI
Rutgers State University	Newark, NJ 07102	P
Rutgers University	Newark, NJ 07102	F
San Diego State University	San Diego, Ca 92182-0315	RI
San Francisco State University	San Francisco, CA 94132	RI
Sienna College	Laudonville, NY 12211	RI
Southern Utah State College	Cedar City, UT 84720	P, V
Sportvagen 33	Sweden	RI
St. Joseph's University	Philadelphia, PA 19131	RI
Stanley Hughes	Yakima, WA 98901	RI
Stevens Institute of Technology	Hoboken, NJ 07030	RI

School or Individual	City State Zip	Degree of Implementation
SUNY Buffalo	Buffalo, NY 14260	RI
SUNY College at Cortland	Cortland, NY 13045	RI
Technical Education Research Centers	Cambridge, MA 02138	RI, P
Telluride High School	Telluride, CO 81435	P
Temple University	Philadelphia, PA 19122	RI
Temple University	Philadelphia, PA 19122	RI
Texas A&M	College Station, TX 77843	RI
The Cooper Union	New York, NY 10003	RI
The School of the Ozarks	Pt. Lookout, MO 65726	RI
The University of North Carolina	Greensboro, NC 27412-5001	RI
The University of West Florida	Pensacola, FL 32514-5751	RI
Tom Cochran	Albany, OR 97321	RI
Towson State University	Baltimore, MD 21204	RI
Troy State University	Dothan, AL 36302	F, V
Tufts University	Medford, MA 02155	RI, V
U.S. Coast Guard Academy	New London, CT 06320	P
U.S. Military Academy	West Point, NY 10996	RI
UCLA	Los Angeles, CA 90024	RI
Universita' di Napoli	80125 Napoli, Italy	RI
University City High School	St. Louis, MO 63104	RI
University of Akron	Akron, OH 44325	P
University of Arizona	Tucson, AZ 85721	RI
University of California	Berkeley, CA 94720	RI
University of California	Berkeley, CA 94720	P
University of California, Berkeley	Berkeley, CA 94720	F
University of Chicago	Chicago, IL 60637	P
University of Chicago	Chicago, IL 60637	P
University of Chicago	Chicago, IL 60637	P
University of Hartford	West Hartford, CT 06117	RI
University of Hawaii at Manoa	Honolulu, HI 96822	RI
University of Kentucky	Lexington, KY 40506-0027	RI
University of Leicester	Leicester LE1 7RF England	RI
University of Louisville	Louisville, KY 40292	RI, V
University of Maryland	College Park, MD 20742	P
University of Maryland	College Park, MD 20742	P
University of Maryland Eastern Shore	Princess Anne, MD 21853	RI
University of Melbourne	Australia 3052	RI
University of Michigan	Pontiac, MI 48053	RI
University of New England	Biddleford, ME 04005	RI
University of Oregon	Eugene, OR 97403-1274	P
University of Prince Edward Island	Canada CJA-4P3	P
University of South Carolina	Columbia, SC 29208	RI
University of Toronto	Scarborough, ONT MIC 1A4	RI
University of Washington	Seattle, WA 98195	RI
University of West Florida	Pensacola, FL 32514	RI
Vassar College	Poughkeepsie, NY 12601	RI
Vernier Software	Portland, OR 97225	RI
West Virginia University	Morgantown, WV 26506	RI
Western Maryland College	Westminster, MD 21157	RI
Whitman College	Walla Walla, WA 99362	RI
Wilmington College	Wilmington, OH 45177	RI
Youngstown State University	Youngstown, OH 44555	P, V

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