CALCULUS-BASED PHYSICS WITHOUT LECTURES

Computer tools and kinesthetic apparatus play key roles in a novel approach to introductory physics that takes into account both time-honored ideas about learning and findings from recent educational research.

Priscilla W. Laws

Every fall several hundred thousand students enroll in calculus-based "engineering" physics courses throughout the United States. Informal statistics tell us that over half of them will fail to complete the sequence of introductory courses. These students complain that physics is hard and boring. The most compelling student critique of traditional introductory physics and chemistry courses comes from college graduates in the humanities who were engaged by Sheila Tobias to take introductory science for credit.[1] These students paint a devastating portrait of introductory courses as uninteresting, time consuming, narrowly fixated on the procedures of textbook problem solving, devoid of peer cooperation, lacking in student involvement during lectures, crammed with too much material, and biased away from conceptual understanding.

Why aren't students who take introductory science doing better? Why are they turning away? It is tempting for frustrated introductory physics instructors to seek simple answers such as "High schools are no longer doing their job" or "If students were only smarter and willing to work harder, we could teach them successfully." There are probably many reasons for the apparent decline in performance of introductory physics students: A larger percentage of 18-year-olds are enrolling in colleges; many state universities have open-admissions policies; there is a shortage of properly trained high school teachers; college-bound high school students spend less than one hour a day studying; they come to physics with little experience working with their hands; there are more extracurricular activities and campus jobs to distract college students from academics; and so on. Whatever the reasons, most instructors agree that at present many introductory physics students seem unprepared and unmotivated.

Workshop Physics philosophy

At Dickinson College we have attempted to analyze the problems associated with the teaching of calculus-based courses, to set new goals and to achieve these goals by changing the way we teach. After receiving a three-year grant from the Department of Education's Fund for the Improvement of Postsecondary Education, John Luetzelschwab, Robert Boyle, Neil Wolf and I began planning the Workshop Physics program at Dickinson College in the fall of 1986, in collaboration with Ronald Thornton from the Tufts University Center for the Teaching of Science and Mathematics and David Sokoloff from the

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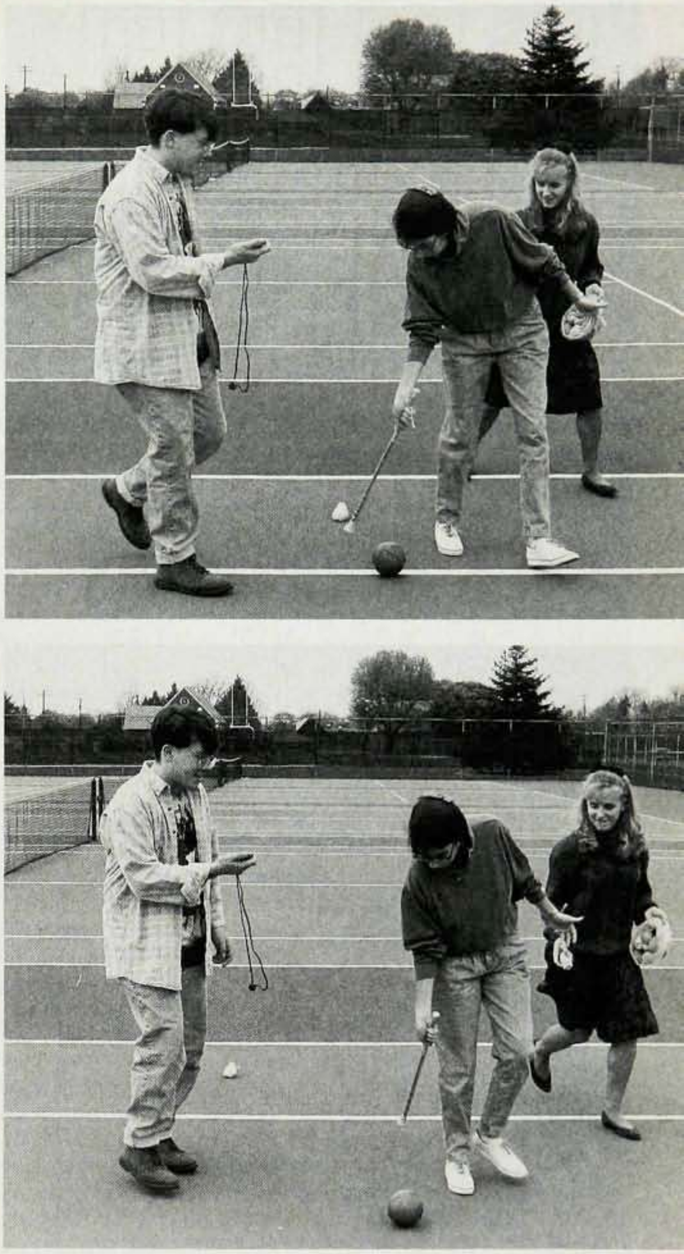


Analog to projectile motion. A Workshop Physics student hits a bowling ball repeatedly in one direction with a baton to approximate a continuous force. Beanbags dropped at regular intervals record locations of the ball. The ball moves with a constant velocity in one direction and constant acceleration in the other, and students obtain a "muscle memory" of having to chase the ball faster and faster.

University of Oregon.

The implicit goals in most traditional introductory physics courses center around teaching students to solve textbook problems. In developing Workshop Physics we assumed that acquiring transferable skills of scientific inquiry is a more important goal than either problem solving or the comprehensive transmission of descriptive knowledge about the enterprise of physics. Arnold Arons refers to this aim as the "development of enough knowledge in an area of science to allow intelligent study and observation to lead to subsequent learning without formal instruction."[2]

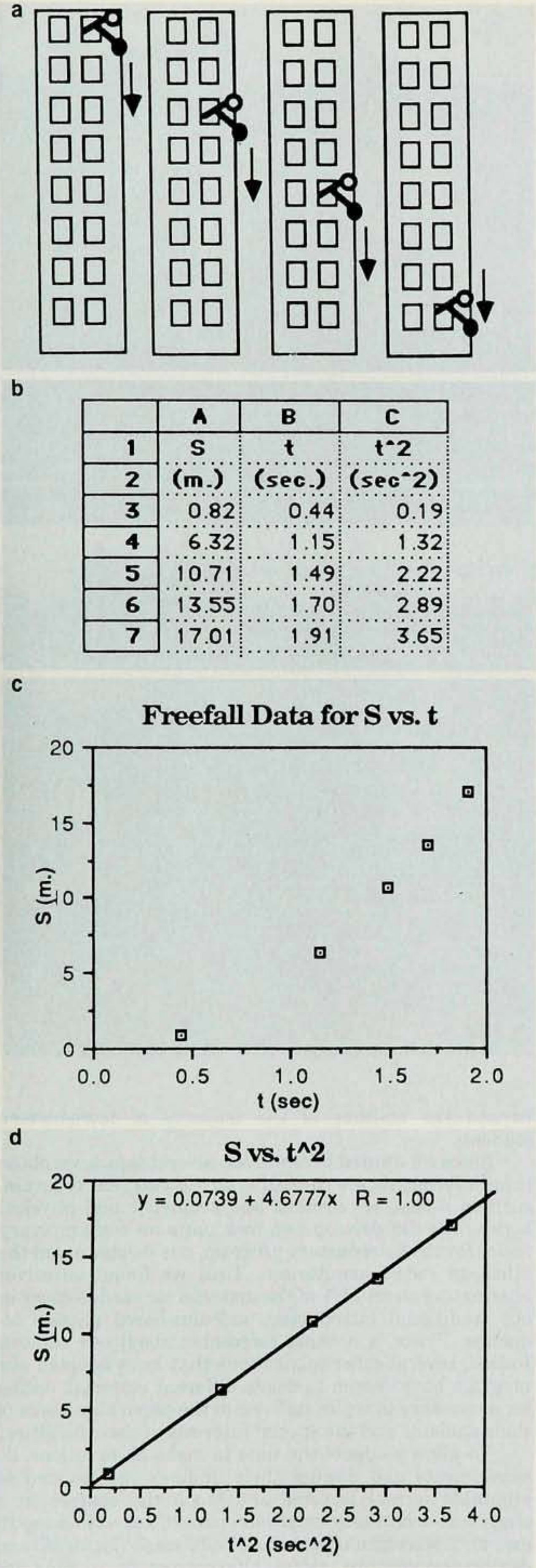
There were two major reasons for emphasizing transferable inquiry skills based on real experience. First, the majority of students enrolled in introductory physics at both the high school and college level do not have sufficient concrete experience with everyday phenomena to comprehend the mathematical representations of them traditionally presented in these courses. The processes of observing phenomena, analyzing data and developing verbal and mathematical models to explain observations afford students an opportunity to relate concrete experience to scientific explanation. The second reason for focusing on the development of transferable skills is that when one is confronted with the task of acquiring an overwhelming body of knowledge, the only viable strategy is to learn some things thoroughly while acquiring methods for independently investigating other things as needed. This approach follows the adage "Less is more."

We incorporated three new elements into our planning: We took findings from science education research into account; we designed and adapted integrated computer tools for the introductory classroom; and we developed devices that allow students to experience motions and forces with their own bodies (kinesthesic apparatus).

We used several criteria in choosing topics to be covered in the Workshop Physics courses. To help students prepare for further study in physics and engineering, we decided to select topics normally covered in the introductory course sequence. Most of these topics involve phenomena that are amenable to direct observation, and the mathematical and reasoning skills needed to analyze observations and experiments in these topics are applicable to many other areas of inquiry. We did not add topics, such as relativity and quantum mechanics, that require levels of abstract reasoning we believe to be beyond the abilities of the majority of introductory students.

Since we wanted to eliminate several topics, we chose to omit those that are covered in our second-year program, such as waves, ac circuits, and geometric and physical optics. We did develop two new units on contemporary topics for the introductory program, one on chaos and the other on radon monitoring. Thus we found ourselves eliminating about 25% of the material we used to cover in our traditional introductory calculus-based physics sequence. There is nothing sacrosanct about our choices. Indeed, several other institutions that have adopted our program have chosen to delete different material, opting for a sequence of topics tailored to the particular needs of their students and the special interests of their faculties.

To allow students the time to make observations, do experiments and discuss their findings, we decided to eliminate formal lectures and teach the courses in a classroom–laboratory environment outfitted with computers and scientific apparatus. Although lectures and demonstrations are useful alternatives to reading for



Linearizing data using spreadsheet and graphing software. **a:** Students drop an object from different heights *S*. **b:** Data are entered into a spreadsheet. **c:** Data are transferred to a graph and plotted. **d:** Vertical distance *S* is plotted as a function of t^2, and the curve is linearized.

	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

transmitting information and teaching specific skills, their value as vehicles for helping students learn how to think, conduct scientific inquiry or acquire real experience with natural phenomena is unproven.[3] In fact, some educators believe that peers are often more helpful than instructors in stimulating original thinking and problem solving on the part of students.[4] Thus we believe that the time students now spend passively listening to lectures is better spent in direct inquiry and discussion with peers. The role of the instructor in our program is to help create the learning environment, lead discussions and encourage students to engage in reflective discourse with one another.

Workshop Physics in practice

Workshop Physics was first taught at Dickinson College during the 1987–88 academic year, to students in both the calculus- and non-calculus-based courses. It is taught in three two-hour sessions each week, with no formal lectures. Each section has one instructor, two undergraduate teaching assistants and up to 24 students. In addition, the workshop labs are staffed during evening and weekend hours by undergraduate teaching assistants.

Pairs of students share the use of a computer and an extensive collection of scientific apparatus and other gadgets. Among other things, students pitch baseballs, whack bowling balls with twirling batons, break pine boards with their fists, pull objects up inclined planes, build electronic circuits, explore electrical unknowns, ignite paper with compressed gas and devise engine cycles using rubber bands.

Hans Pfister, who joined the Workshop Physics teaching staff this fall, has designed a series of carts that students can ride and in which they can experience with their own bodies one- and two-dimensional motions and collisions. The range of kinesthetic experiences available to students is expanding as new apparatus is designed and tested.

The topics have been broken up into units lasting about one week, and students use a specially prepared *Workshop Physics Activity Guide*, which includes exposition, questions and instructions as well as blank spaces for student data, calculations and reflections (see the box on page 29). In general a four-part learning sequence is used: Students begin a week with an examination of their own preconceptions and then make qualitative observations. After some reflection and discussion by the students, the instructor helps with the development of definitions and mathematical theories. The week usually ends with quantitative experimentation centered around verification of mathematical theories. Readings and problems are assigned in a standard textbook, but only after students have discussed phenomena and made predictions and observations in class. In adapting computers for use in Workshop Physics, we have attempted to mimic some of the ways that physicists use computers to understand phenomena. Thus the computer is used in almost every capacity except that of computer-assisted instruction.

Although the MUPPET project at the University of

Maryland has reported great success in teaching introductory students to program in PASCAL (see Gerhard Salinger's article in PHYSICS TODAY, September, page 39), our experience in developing computer-based laboratories at Dickinson has led us to use the spreadsheet as the major tool for calculation. Previous attempts to incorporate a programming language into the introductory lab left us with the feeling that we were using physics to teach computing rather than the other way around.

The computer application most frequently used in Workshop Physics involves the use of spreadsheets for data analysis and numerical problem solving. Data are readily transferred to graphics software with curve fitting routines. (Curve fitting is considered to be one of the essential transferable skills associated with Workshop Physics.) Using the microcomputer for curve fitting, linearization and least-squares analysis, students discover simple functional relationships empirically or verify mathematical theories (see the figure on page 26).

In one unusual application of linearization, a parallel array of nails on a wooden base represents "flux lines" associated with a uniform electric field. The number of nails passing through a wire hoop (used to represent a surface area) as a function of the angle between the hoop's normal vector and the direction of the nails can be counted. Plotting the number of nails subtended versus the cosine of the angle yields a straight line. Thus the students "discover" that flux through an area can be represented as a dot product of the field and the normal vector.

Spreadsheet calculations are also used as a tool for performing numerical integrations. 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 $Y = f(x \pm vt)$.

We are beginning to explore the potential of symbolic and numerical equation solvers in the Workshop Physics program. Students are taught to enter simple commands into Maple, a computer algebra system capable of symbolic manipulation, to determine integrals, solve simultaneous Kirchhoff's law equations and plot functions. Because we consider the spreadsheet operations to be more obvious to students and less demanding with regard to syntax, we have no plans to expand the use of programs like Maple and Mathematica at the introductory level.

Use of MBL tools

As part of the Tools for Scientific Thinking project based at Tufts University, which—like Workshop Physics—is supported by the Education Departments's Fund for the Improvement of Postsecondary Education, Thornton and his colleagues have collaborated with the Workshop Physics staff in the design and testing of hardware and software to allow students to collect and display graphs of data in real time. These microcomputer-based laboratory tools are used extensively in the Workshop Physics program and in high school and university physics courses throughout the United States. An MBL station consists of a sensor or probe plugged into a microcomputer via a serial interface. With appropriate software the computer can perform instantaneous calculations or produce graphs.

The MBL software is used in two ways. First, in cases where the user can observe or control changes in a system directly, the microcomputer is particularly powerful when it is set up to display a real-time graph of the system changes. Thornton and Sokoloff, and Heather Brassell, working independently at the University of Florida, have demonstrated that the use of MBL tools to create real-time graphs yields impressive results in helping students develop an intuitive feeling for the meaning of graphs and for qualitative characteristics of phenomena they are observing.[5] For example, a time trace of the position of one's own body as monitored by an ultrasonic motion detector is unparalleled for learning how the abstraction known as a graph can represent the history of change in a parameter. MBL software has been developed at Tufts for logging motion, force, temperature, sound and voltage data.

In addition, MBL software has been developed at Dickinson for radiation detection and photogate timing. A real-time frequency distribution produced using a Geiger tube with a radioactive source, affords students the same opportunities to explore and develop intuitive notions about both the meaning of frequency distributions and the nature of counting statistics. The MBL photogate software is pedagogically oriented and uses a raw plotter to allow students to see the times when real events switch one or more photogates on or off. A real-time raw plot, which is one of Robert Tinker's many innovative ideas, lends itself to students' discovering how to use operational definitions in the measurement of velocity and acceleration.

Until the past year or so it was difficult for us to streamline the acquisition and analysis of two-dimensional motion data. The availability of computer-based video technology has solved that problem. This fall we began introducing students to computer analysis of motions recorded on videodisc and on student-generated videotapes. We have been collaborating with Jack Wilson at Rennselaer Polytechnic Institute and Joe Redish at the University of Maryland on adapting the video tools under development as part the CUPLE project (see Salinger's article). For example, video analysis is invaluable for studying vertical free-fall and projectile motion. It also makes it possible to track the center of mass of a system of pucks on an airtable or of a high jumper passing over a bar.

In select cases where acquiring real data is not feasible or is too time consuming, we have resorted to the use of simulations. One such simulation is a program developed by David Trowbridge of Microsoft, Graphs and Tracks,[6] which simulates position, velocity and acceleration graphs for a ball rolling down a set of inclined ramps.

Coulomb, a program developed by Blas Cabrera of Stanford University, is capable of displaying electric field lines associated with a collection of charges.[7] Students enjoyed creating strange and unique charge configurations on the computer screen and watching the patterns generated by the field lines. This simulation allowed students to discover that in two-dimensional "Cabreraland," the flux enclosed by a loop is always proportional to the net charge enclosed by the loop. In another simulation, students can analyze the motion of a molecule bouncing around in a two-dimensional box as part of the kinetic theory derivation relating the pressure and volume in a box to the kinetic energy of the molecule.

Using a visual simulation program such as Knowledge Revolution's Interactive Physics package[8] students can create an idealized impulse curve that might result when a pair of rigid objects connected by a spring collides with a wall. They can then compare this idealized curve with the actual impulse curve obtained when a rolling cart collides with a force probe. This exercise provides students with an illuminating glimpse at the process of modeling physical phenomena as idealized systems.

Last but not least, our students use the computer for word processing and creating apparatus drawings for formal laboratory reports. Since we hold written communication skills to be quite important, students are required to hand in a formal lab report each semester. Instructors review these reports carefully and then return them to the students for extensive revisions. Students can create an entire laser-printed lab report, with computer-logged data as well as computer-generated tables, graphs, diagrams and prose, without ever picking up a pencil or pen.

Student learning and attitudes

An extensive program is under way to assess the impact of Workshop Physics activities and teaching strategies on student learning and attitudes at Dickinson College and the University of Oregon. We have administered several conceptual tests and tracked the performance of students on course examinations before and after the Workshop Physics program was instituted at Dickinson. We also have conducted a survey of student attitudes toward the study of introductory physics among about 1600 students at 16 colleges and universities. Here are some of our preliminary findings.

▷ *Students at Dickinson College express a preference for the workshop method of teaching.* Based on the written responses to the college-wide course evaluation forms at Dickinson, about two-thirds of all students who have taken Workshop Physics in our calculus-based courses express a strong preference for the workshop approach over what they imagine the lecture approach to be like. About half the students in the algebra-based courses serving premedical students state a preference for the method.

▷ *In Workshop Physics, a greater percentage of students master concepts that are considered difficult to teach because they involve classic misconceptions.* This improved mastery is demonstrated by improvements in the scores on selected concept-oriented questions developed at Arizona State University, Tufts University, University of Washington and the University of Oregon. These improvements in basic conceptual understanding are the result of students acquiring direct experience with phenomena. For example, a question on the mechanics concepts examination developed at Arizona State University[10] asks students to identify the path of a rocket after its engines have fired at a constant rate (see the figure on page 30). Prior to the introduction of the Workshop Physics program 73% of Dickinson students who had completed the mechanics portion of physics got the wrong answer. Only 31% of students who had completed the mechanics portion of Workshop Physics in the fall of 1983 failed to answer the question correctly. The kinesthetic activity in which students apply "constant" forces by giving moving bowling balls small taps with twirlers' batons gives them a base of experience and allows them to visualize two-dimensional motion in which one dimension has no acceleration and the other dimension undergoes a uniform acceleration (see the figure on page 25).

A senior woman who came to Dickinson as an international studies major and switched to physics described this experience in an oral interview: "The first exam was going to be problems, and I said, 'How can I possibly take an exam which is problems when all we've been doing is playing with toys?' . . . Well, I got the exam, and the first problem was a rocket problem, and it talked about a rocket going up, and it has a constant wind hitting it, and you had to guess the path of the rocket. I have learned nothing about rockets and I'm not a rocket scientist, and so how am I ever going to do this problem? . . . All of a sudden I remembered sitting in the Kline Center with a baton and a bowling ball and hitting this bowling ball, and so if we thought this baton was the wind and the bowling ball was a rocket—wow! I did this problem and I got it right. . . It wasn't in a book or anything, but I saw it in my head."

▷ *Performance of Workshop Physics Students in upper-level physics courses and in solving traditional textbook problems is as good as that of students who took our traditional lecture courses.* For assessment purposes, we devote the same amount of time to textbook reading, homework assignments and textbook-style problems on examinations as we did when teaching traditional courses. Performance is judged based on grades on textbook problems, scores on the problem portions of our introductory examinations, and the impressions of instructors in upper-level courses who are teaching our former students. We see no signs that students' problem-solving skills have diminished.

▷ *We know by observation that students who complete Workshop Physics are considerably more confortable working in a laboratory setting and working with computers.* This competency with the tools of exploration and analysis is often noted by visitors from other institutions who visit our classrooms during the second semester of our two-semester sequence. In the spring of 1988 a freshman 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. . . . Just the experience with the computers and equipment has helped me a lot. I had stayed away from computers and been afraid to play

Sample Exercises from Workshop Physics Unit on Collisions in One Dimension

What's Your Intuition?

Your are sleeping in your brother's room while he is away at college. Your house is on fire, and smoke is pouring into the partially open bedroom door. The room is so messy that you cannot get to the door. The only way to close the door is to throw either a blob of clay or a superball at the door—there's not time to throw both.

What Packs the Biggest Wallop—Clay or the Superball?

Assuming the clay blob and the superball have the same mass, what would you throw to close the door? The clay blob, which will stick to the door, or the superball, which will bounce back at almost the same velocity as it had before it collided with the door? Give reasons for your choice. Remember, your life depends on it.

Observing the Wallop!

Let's check out your intuition by dropping a bouncy ball on a scale and then dropping a dead ball of approximately the same mass on the scale from the same height. We can associate the maximum force on the scale with the maximum force a thrown ball can exert on a door. We would like to investigate how the maximum force is related to the change in momentum of the ball in each case. To do these observations you'll need the following equipment:

▷ a small live ball (of mass m)
▷ a small dead ball or blob of clay (also of mass m)
▷ a platform scale.

As a warm-up to the observations let's consider the mathematics of momentum changes for both inelastic and elastic collisions. Recall that momentum is defined as a *vector quantity* that has both magnitude and direction. Mathematically, momentum change is given by the equation

$$\Delta \mathbf{p} = \mathbf{p}_f - \mathbf{p}_i$$

where $\mathbf{p}_i$ is the momentum of the object just before a collision and $\mathbf{p}_f$ is the momentum of the object just after a collision.

Calculating 1D Momentum Changes

(a) Suppose a dead ball is dropped on a table and "sticks" to the table so that it doesn't bounce. Suppose that just before it bounces it has an initial momentum $\mathbf{p}_i = -p\mathbf{j}$ along the negative y axis where $\mathbf{j}$ is a unit vector pointing along the positive y axis. What is the final momentum of the ball in the same vector notation?

(b) What is the *change* in momentum of the ball as a result of the collision of the ball with the table? Use the same type of **i**,**j**,**k** vector notation to express your answer.

$\Delta \mathbf{p} =$

(c) Suppose a live ball is dropped on a table and "bounces" on the table in an elastic collision so that it doesn't lose any kinetic energy. Suppose that just before it bounces it has an initial momentum $\mathbf{p}_i = -p\mathbf{j}$ along the negative y axis where $\mathbf{j}$ is a unit vector pointing along the positive y axis. What is the final momentum of the ball in the same vector notation? **Hint:** Does the momentum vector point along the $+$ or $-y$ axis?

(d) What is the *change* in the momentum of the ball as a result of the collision of the ball with the table? Use the same type of **i**,**j**,**k** vector notation to express your answer. **Hint:** The answer is not zero. Why?

$\Delta \mathbf{p} =$

around with equipment before, but now I'm not and I can just dig in."

Our attitudes survey indicates that students feel more positive about the mastery of computer applications than any other aspect of the Workshop Physics courses. Students view computer skills as useful in many contexts outside of physics.

▷ *Students in Workshop Physics rate a whole range of learning experiences more highly than their cohorts taking traditional courses.* For example, when students are asked to assess the value of 15 learning opportunities, including attending lectures, using computers, watching demonstrations, solving textbook problems and doing experiments, Workshop Physics students rate all except working out text problems, reading the textbook and attending lectures more highly than do students taking introductory physics courses at other liberal arts colleges. They express significantly more positive feelings about the value of observations and laboratory experiments than students taking traditional courses do. This difference reflects the fact that more observational and experimental activities are available to Workshop Physics students and that performance of these activities counts for a larger proportion of their grade.

Negative feedback

In addition to positive outcomes from Workshop Physics, we have encountered several problems.

▷ *Some students complain that Workshop Physics courses are too complex and demand too much time.* The students reported that in addition to the six hours in class each week, they spent an average of seven hours outside of class to complete activities and assignments. On polling students at 16 other colleges, we discovered that six-and-a-half hours of outside activity was the median for their courses.

We remain undisturbed about the time demands the Workshop Physics course makes on students; however, we do not want the courses to be overwhelming for our less able students. We recognize that even in Workshop Physics courses in which the number of topics covered has been reduced, a wider range of learning abilities is required than in traditional courses. These include reading textbooks, solving problems, mastering computer applications, observing, experimenting, discussing material with peers, composing essays, doing mathematical derivations, analyzing data, and writing and revising formal laboratory reports.

We continue to struggle to eliminate less essential material and to simplify the demands on our students and ourselves without losing the educational advantages we feel we have achieved.

▷ *A small percentage of students thoroughly dislike the active approach.* Some students state emphatically that they would prefer a return to the lecture approach. Although the vast majority of freshmen prefer the workshop approach, roughly half of the upper-class chemistry majors express a desire to have us return to the lecture method.

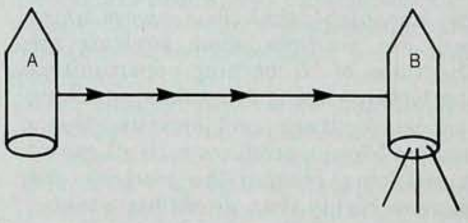
One junior pre-health student wrote on a course evaluation: "It was discouraging to know that if I didn't like the format of teaching of this course . . . there was not another being taught in a different format that I could switch into. . . . There needs to be more lecturing. . . . We don't need to do so much experimenting to derive equations. . . . I need textbook questions with textbook equations to solve anything that's not intuitive. . . . I spent so much time doing out of class work that my other classes suffered and for that I am resentful."

Many of the students who think they would prefer lectures resent having to "teach themselves everything." Fortunately students who have always depended on passive learning and memorization to succeed in courses constitute only a small percentage of our students. Although the percentage of such students is less than the percentage of students who used to be hostile toward our traditional lecture-based courses, we are attempting to achieve a better understanding of why some Workshop Physics students feel so negatively.

▷ *The conceptual gains of students are sometimes disappointing.* Although we have reported with pride on selected conceptual gains, in other areas we apparently need to give much more attention to appropriate curricular changes. For example, we were disappointed to find that students at the University of Oregon who completed Workshop Physics laboratories on circuits did not do significantly better on a number of questions than students who only enrolled in the lecture part of the course. We have noted among students at both Dickinson and the University of Oregon that they have several of the same preconceptions Lillian McDermott's physics education group at the University of Washington has discovered and successfully overcome. One of the most interesting is the tendency of students to visualize a battery as a constant-current source even after they have learned how to use Ohm's law to analyze simple dc circuits mathematically (see the figure on page 31). We are looking forward to consulting with McDermott's group on restructuring our activities to take these preconceptions about circuits into account.

This process of experimenting with student learning, developing theories and designing new instructional strategies is not unlike physics research. It can be rewarding and exciting as well as frustrating.

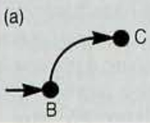
▷ *It is difficult to learn to teach in a workshop format.* The transformation of instructors from authorities who deliver didactic lectures to designers of creative learning environments is extremely challenging. Instructors have to assimilate new understandings of how different students learn and have to break themselves of the habit of winding into long explanations at every turn. We must master the art of nurturing reflective discourse among



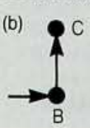
The accompanying figure shows a rocket coasting in space in the direction of the line. Between A and B no outside forces act on the rocket. When it reaches point B, the rocket fires its engines as shown and at a constant rate until it reaches a point C in space.

Which of the paths below will the rocket follow from B to C?

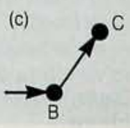
(a)



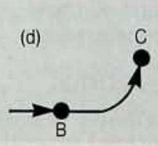
(b)



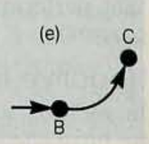
(c)



(d)

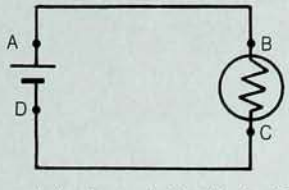


(e)



Rocket problem from a mechanics concepts examination developed at Arizona State University. Students who have taken Workshop Physics answer this question correctly much more often than students from traditional courses.

A bulb and a battery are connected as shown below.



Which is true about the current at various points in this circuit?

A. The current is largest at A.
B. The current is largest at B.
C. The current is largest at C.
D. The current is largest at D.
E. The current is the same at A, B, C and D.
F. The current is the same at A and B; the current is the same at C and D and smaller than at A and B.

Sample circuit problem adapted by David Sokoloff at the University of Oregon from an examination used at the University of Washington. Performance of students on such problems helps Workshop Physics staff improve curricular materials.

students about physics. Since many of us model our teaching instinctively on what our own teachers have provided, it is hard to break out of the traditional mold. We still have a tendency to drone on at times. A junior who took my Workshop Physics course last spring reminded me of this: "Lectures were rarely needed.... Eliminate the talks before class."

Adaptations and outlook

The hardware, software and curricular materials developed for the Workshop Physics and Tools for Scientific Thinking programs are available commercially,[9] and over 400 colleges, universities and high schools have purchased some or all of the materials.

Thornton, Sokoloff and Laws have given a sequence of workshops at both the winter and summer meetings of the American Association of Physics Teachers for the past four years, in cooperation with Pat Cooney of Millersville University (in Millersville, Pennsylvania). One-, two- and three-week-long seminars have been offered to high school, college and university instructors during the past four summers. Over 700 instructors have taken the workshops.

A number of small universities, liberal arts colleges, community colleges and high schools have adopted Workshop Physics programs and dropped formal lecture sessions.

Large universities with high enrollments do not have the personnel and financial resources to adopt the full-blown Workshop Physics program. They can, however, adopt some elements. Edward Adelson, David Andereck and Bruce Patton at Ohio State University, for example, have been attempting to use fewer lectures and more MBL activities in their laboratories. And George Horton, Brian Holton and Chris Borkowski at Rutgers University have used Tools for Scientific Thinking and Workshop Physics activities by having students drop into the school's innovative Math and Science Learning Center.

Sokoloff has adapted the calculus-based Workshop Physics Activity Guide units for use in algebra-based courses at the University of Oregon. He has been coordinating MBL and Workshop Physics laboratory activities with interactive lecture demonstrations.

Our experience with implementing Workshop Physics at Dickinson College and a number of other institutions has been exhilarating, for it represents a blending of time-honored ideas about learning with new laboratory tools and educational technology. The Workshop Physics environment has given students unprecedented power to examine and revise their "common sense" understandings of science in the light of experience and to connect those understandings in a more formal, mathematical framework. At the same time, while we think we have some tentative answers about how to improve the teaching of introductory physics, the Workshop Physics program is far from perfect.

What lies in the future for Workshop Physics and for other programs that might be designed for use at the introductory level? Although the "science of teaching physics" had its origins over 2000 years ago, it has undergone tremendous growth only recently, in tandem with the emergence of new computer tools and new understandings of the learning process and the nature of physics itself. The application of the young science of curricular design to the physics classroom is in its infancy. We have not yet proposed laws of learning, and the outcomes of new teaching strategies are rarely tested.

The nature of our quest as we continue to develop a more scientific approach to teaching was aptly described by philosopher of science Karl Popper when he wrote about science in general, "Its advance is . . . toward an infinite yet attainable aim of ever discovering new, deeper, and more general problems, and of subjecting its ever tentative answers to ever renewed and ever more rigorous tests."[11]

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