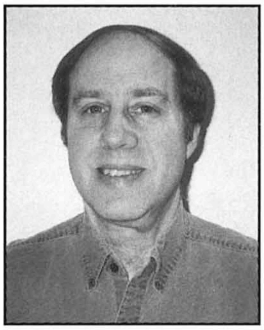
Using Interactive Lecture Demonstrations to Create an Active Learning Environment

By David R. Sokoloff and Ronald K. Thornton



***David R. Sokoloff** is Associate Professor and Associate Head of Physics at the University of Oregon* **_(Department of Physics, University of Oregon, Eugene, OR 97403; sokoloff@oregon.uoregon.edu)._** *His publications include* RealTime Physics *and* Tools for Scientific Thinking. *He was awarded the Distinguished Service Citation from the AAPT in 1996.*

Despite considerable evidence that traditional approaches are ineffective in teaching physics concepts,[1–7] most physics students in the United States continue to be taught in lectures, often in large lectures with more than 100 students. Alternative curricula such as *Workshop Physics* [8,9] that eliminate formal lectures can be used successfully, but substantial structural changes in instruction are required in large universities to implement this program. Some attempts to increase student learning while maintaining existing structures have also been successful. A major focus of the work at the Center for Science and Mathematics Teaching (CSMT) at Tufts University has been on active, discovery-based laboratory curricula supported by real-time microcomputer-based laboratory (MBL) tools. With these tools and curricula, it has been possible to bring about significant changes in the laboratory learning environment at a large number of universities, colleges, and high schools without changing the lecture/laboratory structure and the traditional nature of lecture instruction.[1–3] While these MBL curricula such as *Tools for Scientific Thinking*[10] and *RealTime Physics*[11] do fit easily into existing structures, they also require computers, interfaces, and laboratory space. Many high-school and college physics programs have only a few computers and are unable to support hands-on laboratory work for large numbers of students.

Over the past seven years we have worked at creating successful active learning environments (like those associated with our laboratory curricula) in large (or small) lecture classes. The result of this work, primarily at the University of Oregon and at Tufts University, has been the development of a teaching and learning strategy called *Tools for Scientific Thinking Microcomputer-Based Interactive Lecture Demonstrations (ILDs).*[12]

The ILD Procedure

In 1989, encouraged by our successes in fostering conceptual learning in the introductory physics laboratory,[1–3] we began to explore strategies for using the real-time data displays made possible by MBL tools[13] to establish an active learning environment in the lecture portion of the introductory course. After several years of research, in which we tried different strategies at the University of Oregon, we formalized a procedure for ILD's that is designed to engage students in the learning process and, thereby, convert the usually passive lecture environment to a more active one. The steps of the procedure are:

1. Instructor describes the demonstration and does it for the class without MBL measurements.
2. Students record their names and individual predictions on a Prediction Sheet, which will be collected. (Students are assured that these predictions will not be graded, although some course credit is usually awarded for attendance at these ILD sessions.)
3. Students engage in small-group discussions with their one or two nearest neighbors.
4. Students record their final predictions on the Prediction Sheet.
5. Instructor elicits common student predictions from the whole class.
6. Instructor carries out demonstration with MBL measurements suitably displayed (using multiple monitors, LCD, panel or computer projector).
7. A few students describe the results and discuss them in the context of the demonstration. Option: Students fill out Results Sheet, identical to Prediction Sheet, to take with them.
8. Instructor discusses analogous physical situation(s) with different "surface" features—that is, different physical situation(s) based on the same concept(s).

These steps are performed for each of the simple demonstrations in the sequence of ILD's.

Most students are thoughtful about the individual prediction called for in step 2, and the small-group discussions in a large lecture class are initially quite animated and "on task." After awhile, however, the prediction will be made and discussions may begin to stray. The instructor must observe carefully and pick an appropriate moment to move to the next step. The instructor must also have a definite "agenda" for steps 7 and 8, and must often guide the discussion towards the important points raised by the individual ILD's.

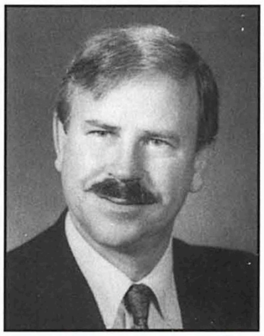
Several other researchers have used a similar procedure to engage their students during lectures. While a few have used actual lecture demonstrations with real data displayed using MBL tools,[14] most use student reasoning or problem solving. A number of these other strategies involve a system that collects individual student responses and feeds them into a computer for display to the instructor and, if desired, to the class. For example, Mazur[15] has reported on his use of such a system in introductory physics lectures at Harvard University. His students are led to conclusions based primarily on reasoning processes, rather than on observations of physical phenomena. Others have made use of a similar student response strategy.[16]

We have used two basic guidelines in designing the short, simple experiments that make up ILD sequences. First, the order and content of the sequences are based on the results of research in physics learning. Our experiences in developing hands-on guided-discovery laboratory curricula and evaluating the learning results have been invaluable in selecting simple but fundamental lecture demonstrations. If the sequences are to be successful, they must begin with what students know and lay the basis for additional understanding. Second, the ILD's must be presented in a manner such that students understand the experiments and "trust" the apparatus and measurement devices used. The real-time display of data gives students feedback in a way that builds confidence in the measurement devices and the resulting data. Many traditional exciting and flashy demonstrations are too complex to be effective learning experiences for students in the introductory class.

For example, in kinematics and dynamics we start with the most basic demonstrations to convince the students that the motion detector measures kinematical quantities (position, velocity, and acceleration) and the force probe measures force in understandable ways. These very basic demonstrations also begin to solidify student understanding of simple kinematics and dynamics concepts before we move on to more complex and concept-rich demonstrations.

ILD Sequences and Newton's Laws

Table I outlines four sequences of ILD's in mechanics that we use to enhance the learning of one-dimensional kinematics and dynamics. The sequences are designed to lead students to a better understanding of Newton laws[17] and make use of the motion detector, force probe, Universal Laboratory Interface (ULI), and *Tools for Scientific Thinking* software (for Macintosh, Windows, MS-DOS comput-



Ronald K. Thornton *is the Director of the Center for Science and Mathematics Teaching and a research professor in the Physics and Education Departments* ***(Departments of Physics and Education, 4 Colby St., Tufts University, Medford, MA 02155; csmt@tufts.edu).*** *He is an author of* RealTime Physics *and* Tools for Scientific Learning. *He has twice served as chair of the National Committee on Research in Science Education of AAPT.*

Table I. Mechanics interactive lecture demonstration sequences.

ILD Sequence	Contents
Kinematics 1: Human Motion	Introductory, constant-velocity kinematics using a motion detector to explore walking motions. Relationships between distance-(position-) and velocity-time graphs.
Kinematics 2: Motion with Carts	Kinematics of constant velocity and uniformly accelerated motion using a motion detector to display motion of a low-friction cart[18] pushed along by a fan unit.[19] Relationships between velocity and acceleration.
Newton's First and Second Laws	Dynamics using a force probe and motion detector to measure forces applied to low- and high-friction carts, and the resulting velocity and acceleration. Relationships among velocity, acceleration, and force.
Newton's Third Law	Using two force probes allows students to examine interaction forces between two objects during fast collisions and when one object is in constant contact with another, pushing or pulling.

ers).[13] Each sequence was designed to be completed in approximately 40 minutes, although more time can be profitably spent (if available) discussing the results with students.

As an example, the ILD sequence for Newton's first and second laws is shown in Fig. 1 and an excerpt from the student Prediction Sheet for this sequence is given in Fig. 2. Figure 3 shows graphs of a typical set of data for Demonstration #6 of this sequence as displayed in *MacMotion*. A force probe mounted on the low-friction cart measured the force applied to the cart by a weight attached to a string hung over a pulley (a modified Atwood's machine; see Fig. 1), while a motion detector measured velocity and acceleration. The cart was given a quick push opposite to the force exerted by the hanging weight, it moved toward the motion detector, slowed down, and returned. Shaded portions of the Fig. 3 graphs show the time interval when the cart was moving under the influence of a constant force.

Do Students Learn from ILD's?

Although the *Tools for Scientific Thinking ILD's* have been used in many settings, we have been able to gather the most complete data on student learning at our own institutions. To evaluate student learning we present the results from a subset of the *Force and Motion Conceptual Evaluation* developed to probe student understanding of dynamics.[17] The choices on these carefully constructed multiple-choice questions were derived from student answers on open-ended questions and from student responses in interviews.

In this article, we focus on four sets of questions that investigate student views of force and motion (dynamics) concepts described by Newton's first and second laws, the "Force Sled," "Force Graph," "Cart on Ramp," and "Coin Toss" questions. We present summary pre- and post-instruction results to examine how exposure to ILD's affects student understanding of dynamics. (We discuss the evidence for the validity of the test and the concern that some teachers have about multiple-choice testing elsewhere.[1,2])

Both the Force Sled and the Force Graph questions explore the relationship between force and motion by asking about similar motions, but the two sets of questions are very different in a number of ways. The Force Sled questions, shown in Fig. 4, refer to a sled on ice (negligible friction) pushed by someone wearing spiked shoes. Different motions of the sled are described, and students are asked to select the force that could cause each motion from seven different force descriptions. The Force Sled questions make no reference to graphs, make no overt reference to a coordinate system, use "natural" language as much as possible, and explicitly describe the force acting on the moving object. The choices are in a completely different format from the graphical displays that the students observe during the ILD's. We will refer to the composite

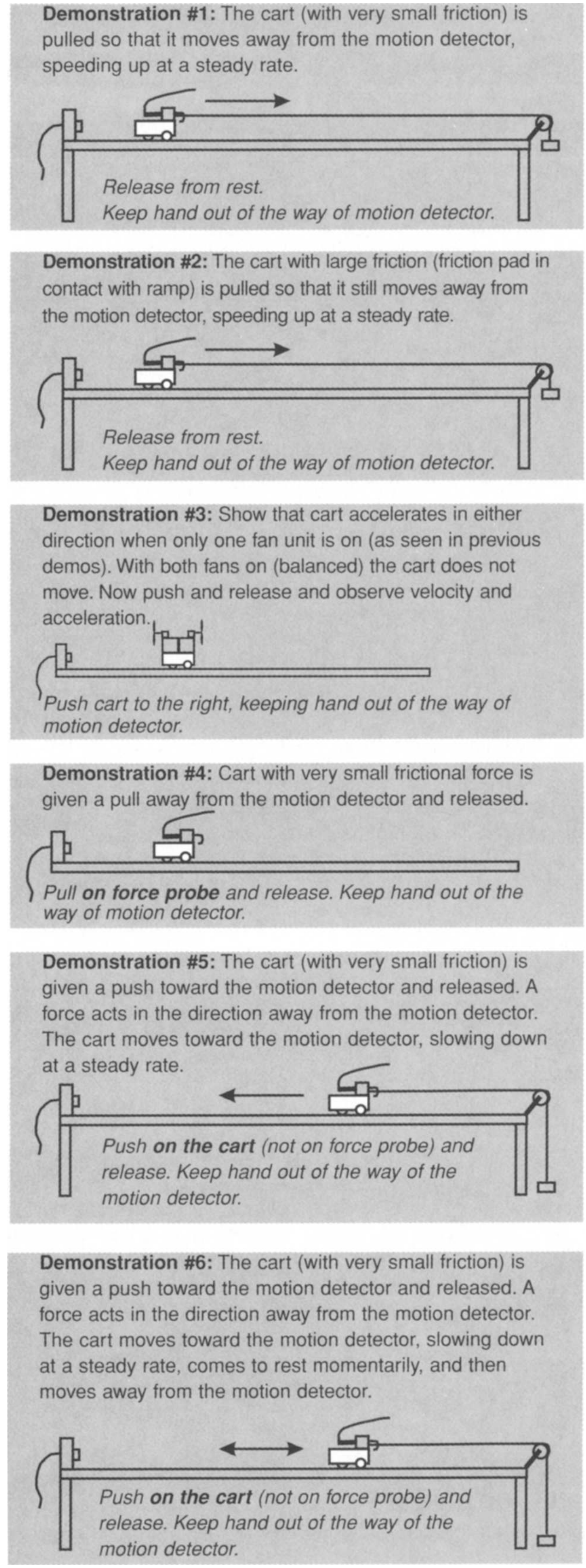
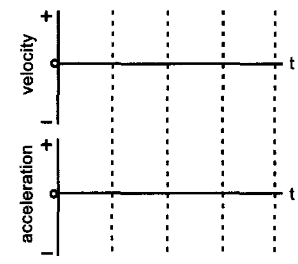


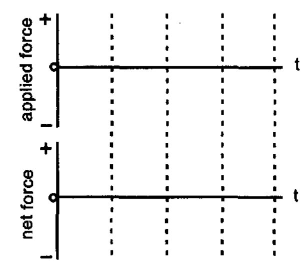
Fig. 1. ILD sequence for Newton's first and second laws. Descriptions of demonstrations taken from ILD teacher materials.

Interactive Lecture Demonstration Prediction Sheet— Newton's First and Second Laws

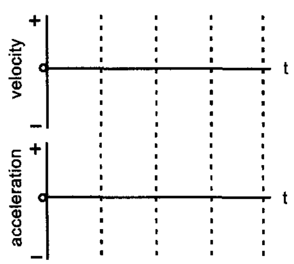
Directions:** This sheet will be collected.* ***Write your name at the top to record your presence in this class. *Follow your instructor's directions. You may write whatever you wish on the other sheet, which is the Results Sheet, and take it with you.*



Demonstration #1: The frictional force acting on the cart is very small (almost no friction) and can be ignored. The cart is pulled with a constant force (the applied force) so that it moves away from the motion detector, speeding up at a steady rate (constant acceleration). Sketch on the axes on the right your predictions of the velocity-time, acceleration-time, and applied and net force-time graphs for this motion. (Applied and net force are the same in this case. Why?)



Demonstration #2: The frictional force acting on the cart is now increased. The cart is pulled with a constant force (the applied force) so that it moves away from the motion detector, speeding up at a steady rate (constant acceleration). Sketch on the same axes to the right your predictions of the velocity-time, acceleration-time, and applied and net force-time graphs for this motion. (Note that the applied and net forces are different now. Which determines the acceleration?) We are measuring only the applied force.



Demonstration #3: The cart has equal and opposite forces acting on it. The frictional force is very small (almost no friction) and can be ignored. The cart is given a quick push away from the motion detector and released. Sketch on the left your predictions of the velocity-time and acceleration-time graphs for the motion after it is released.

Fig. 2. First part of a student prediction sheet. Sheet is collected, and students get credit if it is filled out. Predictions are not graded.

of student responses on a set of these questions as the *Natural Language Evaluation* of student understanding.

Unlike the Force Sled questions, the Force Graph questions use a graphical representation. Students pick the appropriate force-time graph (from nine choices) to describe the force that could cause a toy car to move in various ways on a horizontal surface. These questions make explicit reference to a coordinate system, and do not explicitly describe the origin of the force that is acting. We will refer to the composite of student responses on a set of these questions as the *Graphical Evaluation* of student understanding. In spite of these differences in the two types of questions, student responses are very similar where there is an exact analog between a Force Sled question and a Force Graph question.

The Coin Toss and Cart on Ramp questions also probe student understanding of Newton's first two laws, and are in general even more difficult for students to answer correctly. The Coin Toss questions are shown in Fig. 5. They refer to a coin tossed in the air, and ask students to select from among seven choices the correct description of the force acting on the coin 1) as it moves upward, 2) when it reaches its highest point, and 3) as it moves downward. The Cart on Ramp questions are a coin-toss analog in which a cart is given a push up an inclined ramp, and students are asked to select (again from seven choices) the force acting on the cart during the three parts of its motion: upward, at its highest point, and downward. Note that as with the Force Sled questions, the choices use a non-graphical, natural language format. For each of these sets of questions, students are considered to be understanding only if they choose *all three* forces correctly.

Evaluation at University of Oregon

In the fall of 1991, a series of kinematics and dynamics ILD's were used to enhance learning of Newton's first and second laws in the non-calculus (algebra-trigonometry based) general physics lecture class (PHYS 201) at the University of Oregon. This was a fairly standard introductory physics class except 1) there was no recitation, i.e., the class met for four lectures with approximately 200 students each week, and 2) the introductory physics laboratory is a separate course (PHYS 204), in which about half of the lecture students

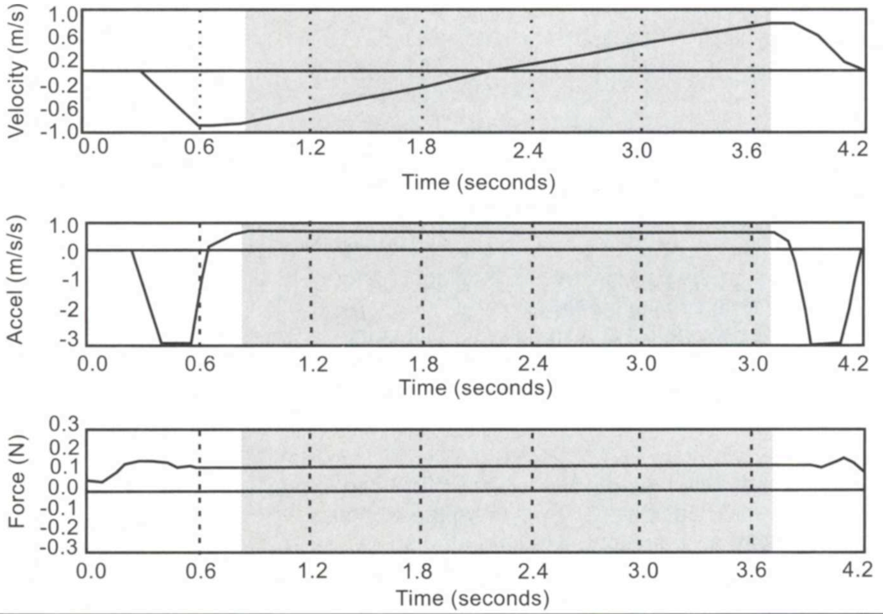


Fig. 3.* MacMotion *display of actual data (Tufts University) from Demonstration #6 in Fig. 1.

were simultaneously enrolled. Thus, the students in the lecture class may be divided into two groups: a NOLAB group enrolled only in the lecture course, and a LAB group enrolled in both the lecture and laboratory courses.

Students at Oregon were first briefly introduced to kinematics with some of the *Human Motion* sequence of ILD's. Next, after all-traditional kinematics instruction, the *Kinematics 2: Motion with Carts ILD* sequence was completed in 40 minutes of one 50-minute lecture. After all-traditional lecture instruction on dynamics, the students experienced the *Newton's First and Second Laws ILD* sequence in 40 minutes of a 50-minute lecture period. Students were awarded a small number of points towards their final grades for attending and handing in their Prediction Sheets on the days when these demonstrations were carried out, but their predictions were not graded.

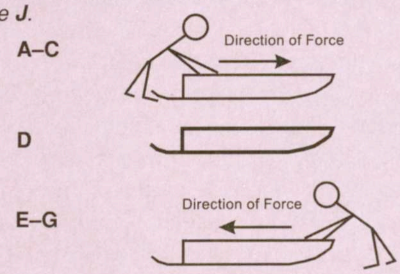
Figure 6 compares student learning of dynamics concepts in traditional instruction (where students listen to lectures, do homework problems, and take quizzes and exams) with learning in the identical course where just 80 minutes of lectures were replaced with ILD's. The baseline for traditional instruction shown in the first two bars in Fig. 6 are the results for 1989–90 Oregon students before and after traditional instruction. (The pre-test results for Oregon students in 1991, and for Tufts students in 1994, shown in Fig. 7, were very similar to this combined 1989–90 group of Oregon students.) As can be seen, all-traditional instruction resulted in only a 7–10% overall improvement on these dynamics questions. In comparison, the last bar shows that the effect of experiencing *less than two full lectures* of ILD's was very substantial for the 1991 Oregon NOLAB group. (Recall that these students *did not* participate in the conceptual laboratories. The addition of ILD's also improved the scores of the LAB students, but most of these students were able to answer the questions correctly after completing just

A sled on ice moves in the ways described in questions 1–7 below. ***Friction is so small that it can be ignored.*** *A person wearing spiked shoes standing on the ice can apply a force to the sled and push it along the ice. Choose the* ***one*** *force (**A** through **G**) that would* ***keep the sled moving*** *as described in each statement below. You may use a choice more than once or not at all but choose only one answer for each blank. If you think that none is correct, answer choice* ***J****.*

A. The force is toward the **right** and is **increasing** in strength (magnitude).
B. The force is toward the **right** and is of **constant** strength (magnitude).
C. The force is toward the **right** and is **decreasing** in strength (magnitude).

D. No applied force is needed.

E. The force is toward the **left** and is **decreasing** in strength (magnitude).
F. The force is toward the **left** and is of **constant** strength (magnitude).
G. The force is toward the **left** and is **increasing** in strength (magnitude).



____1. Which force would keep the sled moving toward the right and speeding up at a steady rate (constant acceleration)?
____2. Which force would keep the sled moving toward the right at a steady (constant) velocity?
____3. The sled is moving toward the right. Which force would slow it down at a steady rate (constant acceleration)?
____4. Which force would keep the sled moving toward the left and speeding up at a steady rate (constant acceleration)?
____5. The sled was started from rest and pushed until it reached a steady (constant) velocity toward the right. Which force would keep the sled moving at this velocity?
____6. The sled is slowing down at a steady rate and has an acceleration to the right. Which force would account for this motion?
____7. The sled is moving toward the left. Which force would slow it down at a steady rate (constant acceleration)?

***Fig. 4. Force Sled questions* (Natural Language Evaluation) *from the* Force and Motion Conceptional Evaluation.**

*Questions 11–13 refer to a coin that is tossed straight up into the air. After it is released it moves upward, reaches its highest point and falls back down again. Use one of the following choices (**A** through **G**) to indicate the force acting on the coin for each of the cases described below. Answer choice **J** if you think that none is correct. **Ignore any effects of air resistance.***

A. The force is **down** and constant.
B. The force is **down** and increasing.
C. The force if **down** and decreasing.
D. The force is zero.
E. The force is **up** and constant.
F. The force is **up** and increasing.
G. The force is **up** and decreasing.

___11. The coin is moving upward after it is released.
___12. The coin is at its highest point.
___13. The coin is moving downward.

***Fig. 5. Coin Toss questions from* Force and Motion Conceptual Evaluation.**

the laboratories.[1,2])

Evaluation at Tufts University

A similar set of ILD's was carried out during the fall of 1994 in the non-calculus introductory physics class (Physics 1) at Tufts University, also with an enrollment of about 200. One difference from Oregon was that at Tufts in 1994 all-traditional instruction in both kinematics and dynamics was completed *before any ILD's were presented.* The timelines at both Oregon and Tufts were necessitated by our desire to assess the effectiveness of the ILD's independently from traditional lecture instruction. All students at Tufts were offered one traditional recitation each week, and all but a few students were enrolled in the laboratory, where they completed two of the active learning (*Tools for Scientific Thinking*) kinematics laboratories but did *not* do any dynamics laboratories.[10]

Because most Tufts students did the two kinematics laboratories, the course began with the *Kinematics 2: Motion with Carts ILD* sequence followed by the *Newton's First and Second Laws ILD* sequence. Both were done in 40 minutes of 50-minute lecture periods. As at Oregon, students were awarded a small number of points towards their final grades for attending and handing in their Prediction Sheets. (At Tufts, an additional 40-minute ILD sequence on Newton's third law was carried out after all traditional mechanics instruction. A preliminary report on the third law instruction can be found in Ref. 2.)

The results of 80 minutes of kinematics and dynamics ILD's on student understanding of Newton's first and second laws are gratifying (see Fig. 7). As at Oregon, our studies show less than a 10% gain for questions like these when students only experience good traditional lecture instruction.

Because of the results at Oregon and Tufts, similar ILD's were repeated at Tufts in the fall of 1995, but this time the ILD's were more integrated into the lectures. There was a different instructor, and the three ILD sequences were given near the beginning of the lectures on kinematics, dynamics, and the third law, respectively, rather than after all lectures. Results were similar to 1994.

Persistence of Learning

Our research data also show that the ILD-enhanced learning is persistent both at Oregon and at Tufts. As a test of retention, the Force Graph questions were included on the Oregon final examination. The final was given about

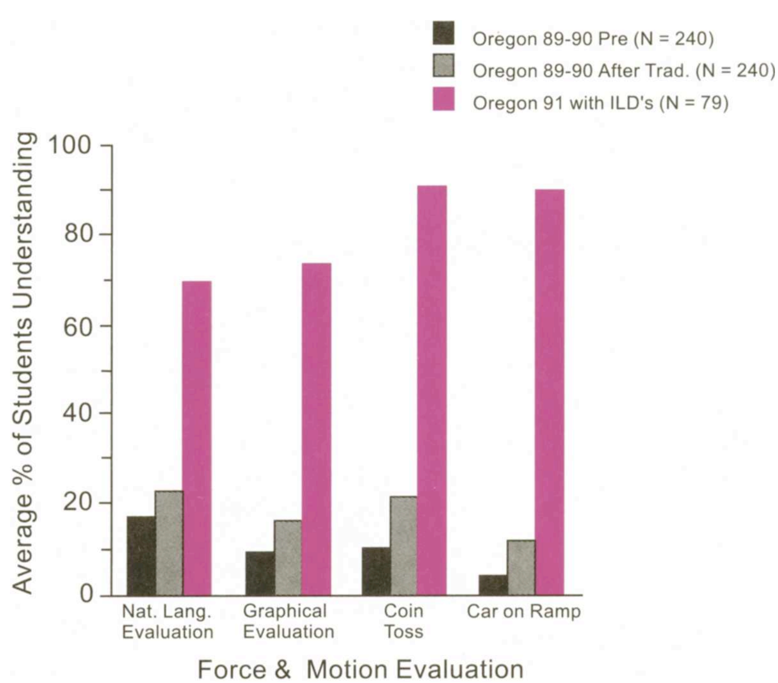


Fig. 6. Comparison of (Oregon) student learning of dynamics before and after traditional instruction (first two bars in each set) with learning when two lectures were replaced with kinematics and dynamics ILD's. Only NOLAB students are included here. See text for discussion.

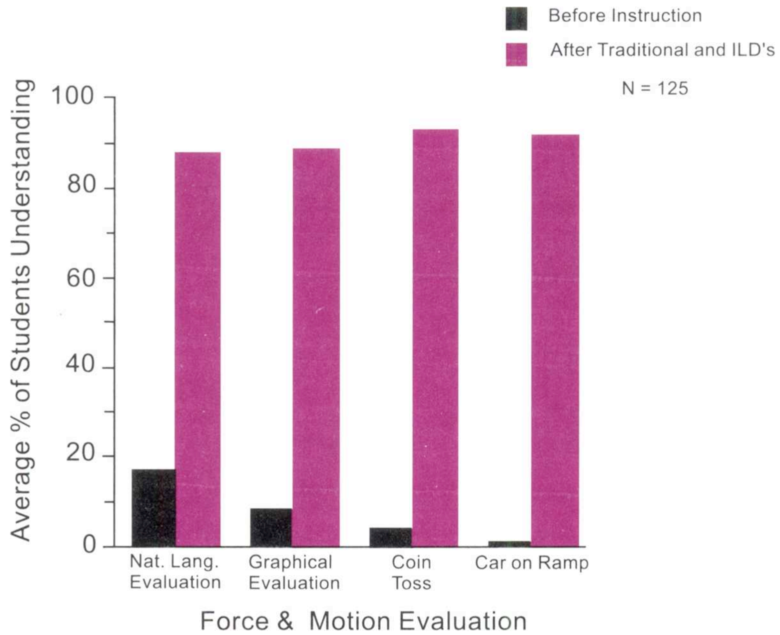


Fig. 7. Comparison of (Tufts, 1994) student learning before and after enhancing the traditional introductory course with kinematics and dynamics ILD's. These students also experienced two* Tools for Scientific Thinking *kinematic labs. See text for discussion.

six weeks after the dynamics ILD's, during which time no additional dynamics instruction took place. There was no decrease in understanding. In fact, there was a 6% improvement in spite of the fact that there is little room for further gain. At Tufts a final exam was given seven weeks after dynamics instruction (including ILD's) had ended. There was a 7% improvement. We have seen student understanding of concepts increase after instruction has ended in many contexts where there has been conceptual learning. We ascribe the increase to assimilation of the concepts by the students. Additional different questions about dynamics were also asked on the final exam at Oregon and Tufts, and more than 90% of the students were able to answer them correctly.

Conclusions

Our studies of student understanding using the research-based *Force and Motion Conceptual Evaluation* with large numbers of students show that introductory physics students do not commonly understand kinematics and dynamics concepts as a result of thorough traditional instruction. This research and that of others (along with the development of user-friendly MBL tools and our experience with computer-supported active laboratory curricula) has allowed us to develop a strategy for more active learning of these concepts in lectures using *Microcomputer-Based Interactive Lecture Demonstrations*. Assessments using the *Force and Motion Conceptual Evaluation* indicate that student understanding of dynamics concepts is improved when these ILD's are substituted for traditional lectures.

Acknowledgments

We are especially grateful to Priscilla Laws of Dickinson College for her continuing collaboration, which has contributed significantly to this work. The curricula we developed would not have been possible without the hardware and software development work of Stephen Beardslee, Lars Travers, Ronald Budworth, and David Vernier. We also thank the physics faculty and students at the University of Oregon and Tufts University for participating in the ILD's and assessments.

This work was supported in part by the National Science Foundation and the Fund for Improvement of Post-Secondary Education (FIPSE) of the U.S. Department of Education.[13]

References

1. R.K. Thornton, "Learning physics concepts in the introductory course, Microcomputer-based labs and interactive lecture demonstrations" in *Proc. Conf. on the Intro. Physics Course*, (Wiley, New York, 1996), pp. 69–85.
2. R.K. Thornton, "Using large-scale classroom research to study student conceptual learning in mechanics and to develop new approaches to learning," in Microcomputer-Based Laboratories: Educational Research and Standards, Series F, Computer and Systems Sciences, Vol. 156, edited by Robert F. Tinker (Springer Verlag, Berlin, Heidelberg, 1996), pp. 89–114.
3. R.K. Thornton and D.R. Sokoloff, "RealTime Physics: Active Learning Laboratory," *Proceedings of the International Conference on Undergraduate Physics Education*, July, 1996, to be published by the American Institute of Physics.
4. L.C. McDermott, "Millikan lecture 1990: What we teach and what is learned—closing the gap," *Am. J. Phys.* **59**, 301–315 (1991).
5. L.C. McDermott, "Research on conceptual understanding in mechanics," *Phys. Today* **37**, 24–32 (July, 1984).
6. D. Hestenes, M. Wells, and G. Schwackhammer, "Force Concept Inventory," *Phys. Teach.* **30**, 141–158 (1992).

7. J. A. Halloun and D. Hestenes, "The initial knowledge state of college physics students," *Am. J. Phys.* **53**, 1043–1056 (1985).
8. P. W. Laws, "Calculus-based physics without lectures," *Phys. Today* **44**:12, 24–31 (December, 1991).
9. P.W. Laws, *Workshop Physics Activity Guide: The Core Volume with Module 1: Mechanics* (New York, Wiley, 1997).
10. R.K. Thornton and D.R. Sokoloff, *Tools for Scientific Thinking—Motion and Force Curriculum and Teachers' Guide*, 2nd ed. (Vernier Software, Portland, 1992).
11. D.R. Sokoloff, R.K. Thornton, and P.W. Laws, *RealTime Physics Mechanics V. 1.40* (Vernier Software, Portland, 1994).
12. This work was supported in part by the National Science Foundation under grant number USE-9150589, *Student Oriented Science*, grant number USE-9153725, *The Workshop Physics Laboratory Featuring Tools for Scientific Thinking*, and grant number TPE-8751481, *Tools for Scientific Thinking: MBL for Teaching Science Teachers*, and by the Fund for Improvement of Post-secondary Education (FIPSE) of the U.S. Department of Education under grant number G008642149, *Tools for Scientific Thinking*, and number P116B90692, *Interactive Physics*.
13. The MBL Motion Detector, Force Probe, Universal Laboratory Interface (ULI) and *Tools for Scientific Thinking* software are described in references 1–4, and are available from Vernier Software, 8565 Beaverton-Hillsdale Highway, Portland, OR 97225-2429.
14. E. Sassi, Department of Physics, University of Naples, Mostra D'Oltremare pad. 20, I80125 Naples, Italy, private communication.
15. E. Mazur, *Peer Instruction: A User's Manual* (Prentice Hall, Upper Saddle River, NJ, 1997).
16. R. Defresne et al., "Classtalk: A classroom communication system for active learning," *J. Comput. Higher Ed.* **7**, 3–47 (1996).
17. Copies of *ILD Mechanics* sequences and teacher's notes are available from Vernier Software, 8565 Beaverton-Hillsdale Highway, Portland, OR 97225-2429. The complete *Force and Motion Conceptual Evaluation* and ILD's under development in other areas of physics are available from the Center for Science and Mathematics Teaching, Tufts University, 4 Colby St., Medford, MA 02155.
18. For example, the dynamics cart available from PASCO scientific, P.O. Box 619011, 10101 Foothills Blvd., Roseville, CA 95678-9011. Observation of motion with adjustable amounts of friction is possible using the Adjustable Friction Pad assembly, also available from PASCO.
19. See R. Morse, "Constant acceleration experiments with a fan-driven dynamics cart," *Phys. Teach.* **31**, 336–338 (1993).