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RealTime Physics: active learning labs transforming the introductory laboratory

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Abstract

Computer-based tools that enable students to collect, display and analyse data in real time have catalysed the design of a laboratory curriculum that allows students to master a coherent body of physics concepts while acquiring traditional laboratory skills. This paper describes *RealTime Physics*, a sequenced introductory laboratory curriculum that is based on the results of physics education research, and uses computer-based tools to facilitate student learning.

(Some figures in this article are in colour only in the electronic version)

Each year in the USA, over 300 000 college and university students pass through introductory physics laboratories designed to help them acquire investigative skills and verify equations already presented in textbooks and lecture sessions. Each year over 800 000 students do similar laboratory exercises in high school classes. The intent of introductory courses is to establish a basis for further study in physics, engineering and other experimental sciences. Instructors also hope to interest students in further study in physics. Although there has been relatively little research on the educational value of weekly physics laboratory sessions [1], we do know that many students find traditional labs tedious and boring. Revitalization of both the lecture and laboratory components of introductory courses is essential to the long-term health of physics as a discipline.

In a traditional introductory physics laboratory, a student typically spends 2 or 3 h a week in the laboratory collecting data, performing calculations and graphing results that verify only one relationship. The time, effort and expense of maintaining laboratory programs, coupled with faculty and student concern about their educational value, has led some universities including prestigious research institutions such as Harvard and MIT to reduce or even abandon introductory laboratories.

Emerging computer technologies and new understanding of student learning difficulties can help us make physics laboratory programs more engaging and effective. In addition, by doing research on learning in laboratory settings, we can establish a basis for continuous improvement of student learning in laboratory programs. In this paper, we document that the *RealTime Physics* laboratory curriculum that we have developed can lead to dramatic improvements in student understanding of vital physics concepts.

Microcomputer-based laboratory tools

Beginning in 1986, new microcomputer-based laboratory (MBL) tools[4] have become increasingly popular for the real-time collection, display and analysis of data in the introductory laboratory. MBL tools consist of electronic sensors, a microcomputer interface, and software for data collection and analysis. Sensors are now available for measuring motion (position, velocity and acceleration), force, sound, magnetic field, current, voltage, temperature, pressure, rotary motion, humidity, light intensity and many other physical quantities.

MBL tools provide a powerful way for students to learn physics concepts. For example, students can discover motion concepts for themselves by walking in front of an ultrasonic motion sensor while the software displays position, velocity and/or acceleration in real time. Students can see a cooling curve displayed instantly when a temperature sensor is plunged into ice water, or they can use a microphone to see how a sound pressure versus time plot changes as one of them sings.

MBL data can also be analysed quantitatively. Students can then obtain basic statistics for all or a selected subset of the collected data and then either fit or model the data with an analytic function. They can also integrate, differentiate or display Fourier transforms of data. A software feature allows students to generate and display *calculated quantities* from collected data in real time. For example, since mechanical energy depends on mass, position and velocity, the time variation of potential and kinetic energy of an object can be displayed graphically in real time. The user just needs to enter the mass of the object and the appropriate energy equations ahead of time.

The need for a new laboratory curriculum

In the mid-1980s we also began to collaborate on the development of curricular materials, apparatus and MBL tools to help students learn physics concepts and skills through guided activities. The design of our curricular materials took the outcomes of physics education research into account. Since then we have been testing and refining our activities based on research on student learning at our own institutions and elsewhere.

Our initial efforts were focused on two curriculum projects: Tools for Scientific Thinking[5] and Workshop Physics [2]. A set of Tools for Scientific Thinking laboratory modules was developed to help students use MBL tools to enhance their understanding of physics concepts in mechanics and thermodynamics. The Workshop Physics curriculum was developed as the basis for a two-semester introductory sequence in which lectures were replaced by hands-on activities [3]. Computer tools were used extensively to help students interpret their

[4] These tools were originally developed at Technical Education Research Centers (TERC) and Tufts University Center for Science and Mathematics Teaching. The most popular current versions in the US are distributed by Vernier Software and Technology (www.vernier.com) and PASCO Scientific (www.pasco.com). Besides probes, they also distribute other appropriate hardware like low-friction dynamics cart and track systems. The latest version for the Vernier software package, *LoggerPro v. 3*, also includes a complete video analysis package.

[5] The *Tools for Scientific Thinking, Motion and Force* and *Heat and Temperature* curricula are available from Vernier Software and Technology, www.vernier.com.

observations. These included MBL tools, spreadsheets and, more recently, digital video analysis software (see footnote 4).

As these curricula were developed, the teaching community was becoming more aware of how students' naive conceptions of the physical world interfere with their learning. For example, consider a ball tossed vertically. Most students who successfully complete introductory physics can use kinematic equations to calculate the exact position and velocity of the ball given its initial velocity and position. Physics education researchers discovered that most of these students retain the belief that there is an upward force and acceleration while the ball is rising, and zero force and acceleration when it is at its highest position. Using an MBL motion sensor we designed activities that allow students to see in real time that the acceleration of a ball is the same during the entire toss. Similarly, while physics students can analyse simple direct current circuits using Ohm's or Kirchhoff's laws, many retain their belief that electrical current is 'used up' in passing through a light bulb or ohmic resistor. Using MBL current probes on either side of a light bulb, students can see that the current is identical on a moment-by-moment basis at both circuit locations, no matter how the voltage applied to the circuit is varied.

Based on the outcomes of physics education research, many high school and college level instructors wanted to enhance conceptual learning in the laboratory while developing their students' quantitative laboratory skills. Many instructors found that the Tools for Scientific Thinking curriculum was not comprehensive enough while adoption of the Workshop Physics curriculum required too many changes in the laboratory environment and in course scheduling. It seemed logical to combine elements from each of these curricula in the development of a new laboratory program.

The *RealTime Physics* curriculum

In 1992 we set out to develop a set of *RealTime Physics* (*RTP*) laboratories, with funding from the National Science Foundation[6]. Four laboratory guides (modules) are currently published by John Wiley and Sons [4]: Module 1: Mechanics, Module 2: Heat and Thermodynamics, Module 3: Electric Circuits and Module 4: Light and Optics.

Each laboratory guide includes activities for use in a series of related laboratory sessions that span an entire quarter or semester. Lab activities and homework assignments are integrated so that they depend on learning that has occurred during the previous lab session and also prepare students for activities in the next session. The major goals of the *RTP* project are to help students: (1) acquire an understanding of a set of related physics concepts; (2) experience the physical world directly by using MBL tools for real-time data collection, display and analysis; (3) develop traditional laboratory skills and (4) master topics covered in lectures and readings using a combination of conceptual activities and quantitative experiments. These goals align well with the goals proposed by the American Association of Physics Teachers (AAPT) for the introductory laboratory [1]. In order to achieve these goals we developed a set of design principles based on educational research. These principles are summarized in table 1.

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[6] This work was supported in part by the National Science Foundation under grant number DUE-9455561, '*Activity Based Physics: Curricula, Computer Tools, and Apparatus for Introductory Physics Courses*', 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 US Department of Education under grant number G008642149, *'Tools for Scientific Thinking'*, and number P116B90692, '*Interactive Physics*'.

Table 1. Design principles for the *RTP* laboratory guides.

RealTime Physics design principles

Each laboratory guide includes activities that

- are sequenced to provide students with a coherent observational basis for understanding a single topic area in one semester or quarter of laboratory sessions
- provide activities that invite students to construct physical models based on observations and experiments
- help students modify their common conceptions about physical phenomena that make it difficult for them to understand powerful general principles of physics
- work well when performed in collaborative groups of two to four students
- incorporate MBL tools so that students can test predictions by collecting and graphing data in real time
- incorporate a learning cycle consisting of prediction, observation, comparison, analysis and quantitative experimentation
- provide opportunities for class discussion of student ideas and findings and
- integrate homework assignments designed to reinforce critical concepts and skills

Table 2. Titles of labs in the four modules of *RTP*.

RealTime Physics table of contents

Module 1: Mechanics
- Lab 1: introduction to motion
- Lab 2: changing motion
- Lab 3: force and motion
- Lab 4: combining forces
- Lab 5: force, mass and acceleration
- Lab 6: gravitational forces
- Lab 7: passive forces and Newton's laws
- Lab 8: one-dimensional collisions
- Lab 9: Newton's third law and conservation of momentum
- Lab 10: two-dimensional motion (projectile motion)
- Lab 11: work and energy
- Lab 12: conservation of energy

Module 2: Heat and Thermodynamics
- Lab 1: introduction to heat and temperature
- Lab 2: energy transfer and temperature change
- Lab 3: heat energy transfer
- Lab 4: the first law of thermodynamics
- Lab 5: the ideal gas law
- Lab 6: heat engines

Module 3: Electric Circuits
- Lab 1: batteries, bulbs and current
- Lab 2: current in simple dc circuits
- Lab 3: voltage in simple dc circuits and Ohm's law
- Lab 4: Kirchhoff's circuit rules
- Lab 5: introduction to capacitors and RC circuits
- Lab 6: introduction to inductors and LR circuits
- Lab 7: introduction to ac currents and voltages
- Lab 8: introduction to ac filters and resonance

Module 4: Light and Optics
- Lab 1: introduction to light
- Lab 2: reflection and refraction of light
- Lab 3: geometrical optics: lenses
- Lab 4: geometrical optics: mirrors
- Lab 5: polarized light
- Lab 6: waves of light

The core activities for each laboratory session can be completed in 2 h. Extensions provide more in-depth coverage when longer lab periods are available. The materials are comprehensive enough so that students can use them effectively even in settings where instructors and teaching assistants have minimal experience with the curricular materials.

Table 2 lists the labs contained in each of the four modules of *RTP*. The curriculum is distributed in both print and electronic formats. The latter allows instructors to make local modifications and reprint those portions that are suitable for their equipment and programs.

A case study: RealTime Physics Mechanics

In order to illustrate the essential features of the *RTP* laboratory curricula, we will discuss the *Mechanics* curriculum in more detail. According to sales statistics from the publisher, as of

Fall 2006, *RTP Mechanics* has been adopted by 58 colleges and universities in the USA. This represents about 15 000 introductory physics students. (The actual number of users is believed to be considerably higher, since earlier editions were distributed nearly free of charge before the current editions were published by Wiley.)

The primary goal is to help students achieve a solid understanding of classical mechanics including Newton's three laws of motion. Physics education researchers have discovered that a majority of physics students begin their study of mechanics with preconceptions about the nature of motion. Most students have a great deal of difficulty understanding Newton's laws, if they are not challenged to test the viability of their preconceptions.

Newtonian dynamics is basically a study of the relationship between forces and motion. The simultaneous use of an MBL force probe and motion sensor is powerful because students can display force–time graphs in real time along with any combination of graphs of position, velocity and/or acceleration versus time. The availability of low-friction dynamics cart and track systems (see footnote 4) makes it possible for students to study the relationship between applied forces and resulting motions in simple cases where friction forces are essentially negligible.

As an example of the approach taken in *RTP Mechanics*, let us consider a critical MBL activity taken from Lab 3 on relating force and motion. After a careful study of kinematics and the development of a force scale in previous lab activities, students are asked to predict how force and motion are related. Next they discuss their predictions in their lab groups. Many students believe that when a force is exerted on an object, the object will move with a velocity that is proportional to the net applied force. This fundamental preconception that there is a proportional relationship between force and velocity is a major impediment to understanding Newton's second law.

Students are asked to test their force–motion predictions by mounting their calibrated force probe on a low-friction cart. Then they can push and pull on the cart–force probe system to create a variable force on it while the velocity and acceleration of the cart are recorded using a motion sensor, as shown in the laboratory write-up for this activity in figure 1. A typical set of real time velocity–, force– and acceleration–time graphs is shown in figure 2. It is clear that on a moment-by-moment basis, it is acceleration and not velocity that is proportional to the force applied to the low-friction dynamics cart.

The students then go on to examine the relationship between applied force and acceleration (Newton's second law) quantitatively, using a modified Atwood's setup in which a string attached to a falling mass applies a constant force to the force probe mounted on the low friction cart.

Evaluating the effectiveness of the *RealTime Physics Mechanics* laboratory curriculum

How effective is *RTP Mechanics* in helping students understand Newton's Laws of motion? To evaluate student learning in dynamics we developed the research based, multiple-choice examination called the *Force and Motion Conceptual Evaluation (FMCE)* [5, 6][7]. Responses on open-ended written questions and during interviews were used to identify basic mechanics concepts that students find difficult, and multiple choice questions were developed based on these.

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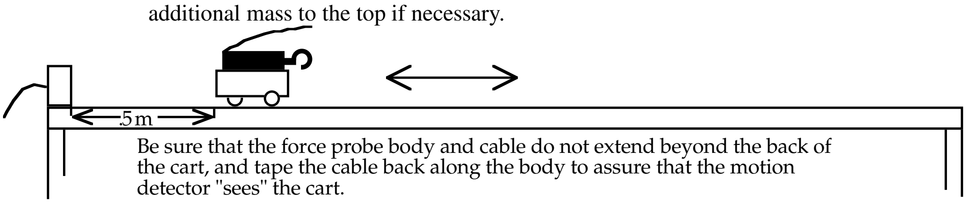
[7] The *FMCE* and conceptual evaluations in other topic areas can be found at the Workshop Physics website http://physics.dickinson.edu/~wp_web/wp_resources/wp_assessment.html.

Activity 2-1: Pushing and Pulling a Cart

In this activity you will move a cart by pushing and pulling it with your hand. You will measure the force, velocity and acceleration. Then you will be able to look for mathematical relationships between the applied force and the velocity and acceleration, to see whether either is (are) related to the force.

1. Set up the cart, force probe and motion detector on a smooth level surface as shown below. The cart should have a mass of about 1 kg with force probe included. Fasten additional mass to the top if necessary.



Be sure that the force probe body and cable do not extend beyond the back of the cart, and tape the cable back along the body to assure that the motion detector "sees" the cart.

The force probe should be fastened securely to the cart so that the body and cable do not extend beyond the end of the cart facing then motion detector. (Tape the cable from the force probe back along the body to assure that it will not be seen by the motion detector.)

Prediction 2-1: Suppose you grasp the force probe hook and move the cart forwards and backwards in front of the motion detector. Do you think that either the velocity or the acceleration graph will look like the force graph? Is either of these motion quantities related to force? (That is to say, if you apply a changing force to the cart, will the velocity or acceleration change in the same way as the force?) Explain.

2. To test your predictions, open the experiment file called **Motion and Force (L3A2-1)**. This will set up velocity, force and acceleration axes with a convenient time scale of 5 sec, as shown below. **Calibrate** the force probe using a 2.0 N pull from a spring scale, if you haven't already done this in Activity 1-4.

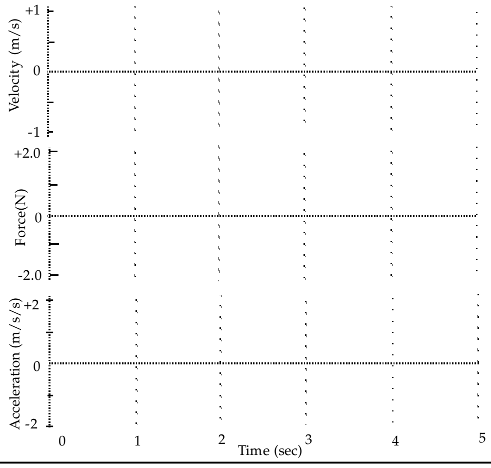


Figure 1. Excerpt from investigation 2 of *RTP Mechanics* lab 3 which illustrates that acceleration—not velocity—is proportional to force.

The *FMCE* has been administered before instruction (pre-test) and after instruction (post-test) to many high school and college level students. However, we have done our most extensive controlled testing at the University of Oregon, in the algebra–trigonometry-based general physics course and separate introductory laboratory course, and at Tufts University in the calculus-based course.

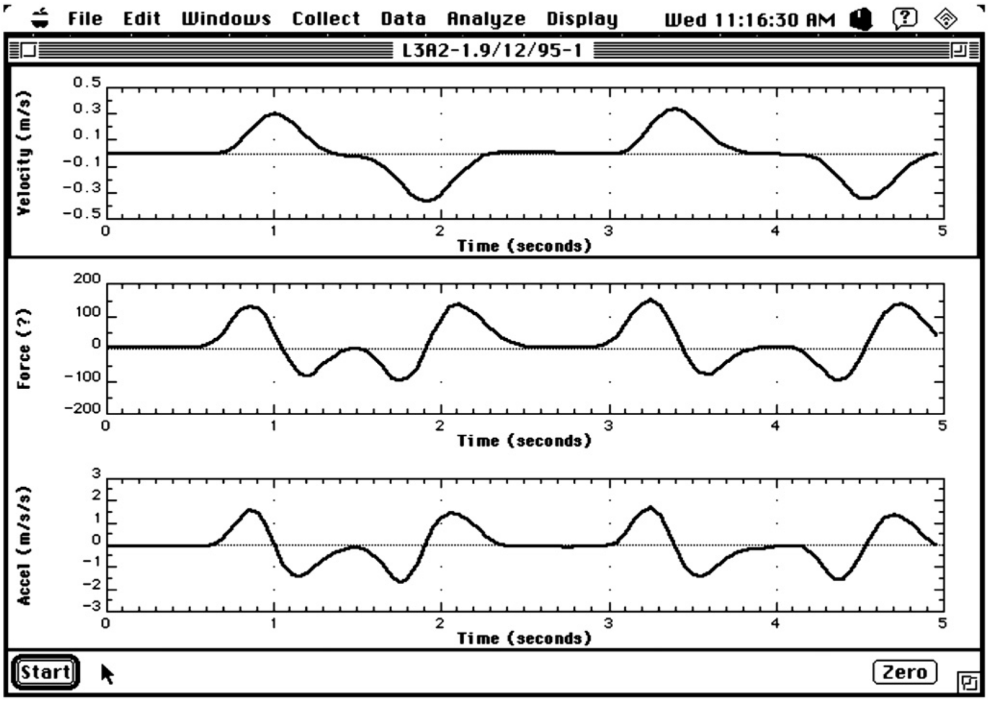
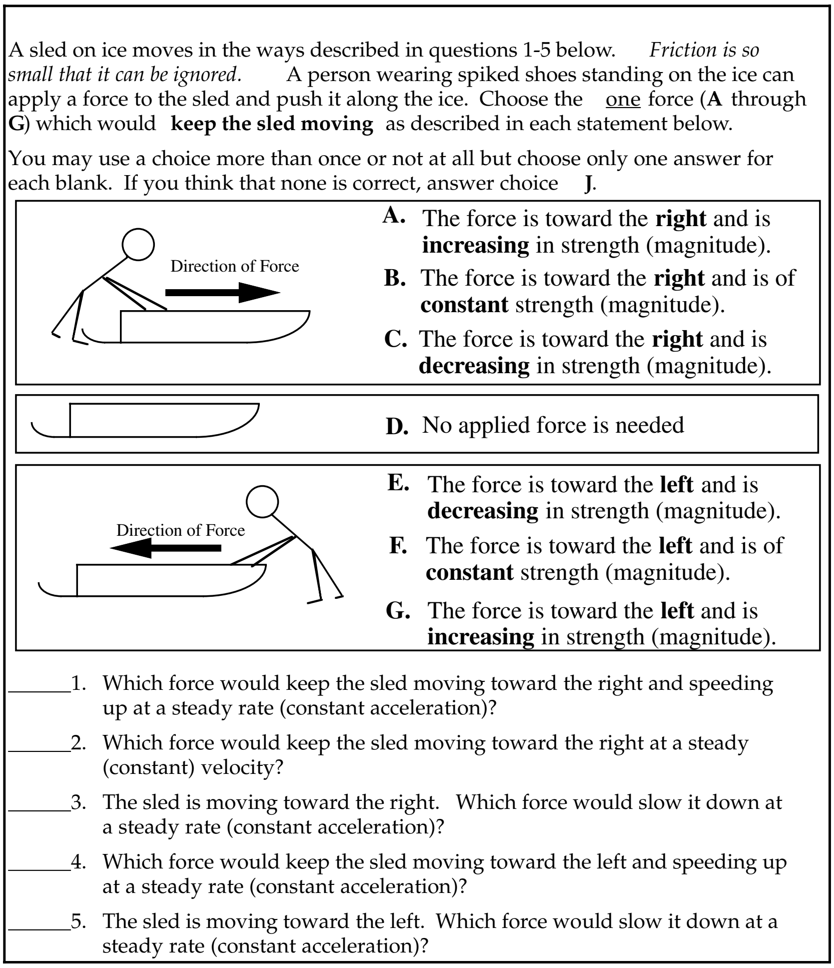


Figure 2. Velocity–, force– and acceleration–time graphs for a low-friction cart pulled away from the motion sensor beginning at about 0.6 s and then quickly stopped, then pushed back towards the motion sensor beginning at about 1.6 s and again quickly stopped, as in *RTP Mechanics* lab 3, activity 2-1. The pulls and pushes are repeated beginning at about 3.1 s.

By examining pre- and post-test results we can illustrate how the *RTP* laboratory affects student understanding of dynamics. For example, two sets of questions explore the relationship between force and motion by asking about similar motions in two different ways. The first is a series of 'Force Sled' questions (see figure 3) that can be used to gauge how well students can understand natural language descriptions of motion. The 'Force Graph' questions (see figure 4) are intended to measure whether or not students can understand graphical descriptions of the *same* motions.

The Force Sled questions (Natural Language evaluation) are written in natural language and make no reference to graphs or coordinate systems. The force acting on a moving object is described explicitly. On the other hand, the Force Graph questions (graphical evaluation) make explicit references to coordinate systems, and do not explicitly describe the force that is acting. In spite of these differences in the questions, student responses are very similar whenever there is an exact analogue between a Force Sled question and a Force Graph question.

During 1989 and 1990, 240 students in the Oregon algebra–trigonometry-based lecture class were not also enrolled in the separate introductory laboratory course. Figure 5 shows the percentage of these students who answered the Natural Language questions and Graphical questions in a Newtonian way both before and after traditional instruction on dynamics that included standard lectures, homework problems, quizzes and examinations. To make precise comparisons, the identical questions were asked before and after instruction. These results show that fewer than 20% of students answered dynamics questions in ways that are consistent



A sled on ice moves in the ways described in questions 1-5 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**) which 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 is moving toward the left. Which force would slow it down at a steady rate (constant acceleration)?

Figure 3. A selection of Force Sled (Natural Language) questions from the *Force and Motion Conceptual Evaluation* that probe student understanding of Newton's first and second laws using natural language.

with a Newtonian view of the world either before or after traditional instruction. Also, the normalized learning gain from pre to post-instruction was less than 10%.[8]

We need to emphasize that these results are typical, and not unique to the University of Oregon. Our findings are consistent with other research into student understanding of dynamics. The fact that traditional instruction has little effect on student beliefs about force and motion is confirmed by research involving thousands of students enrolled in traditional introductory physics courses [5–9] (see footnote 7).

How well do students understand dynamics concepts after completing *RTP Mechanics* laboratories? Figure 6 shows the results for groups of University of Oregon students who were enrolled in both lecture and the *RTP Mechanics* laboratory during 1992, 1993 and 1994. The improvement based on their laboratory work is dramatic. (No pre-test was given in these years, but the average pre-test results in 1989–1991 are included for comparison.) These

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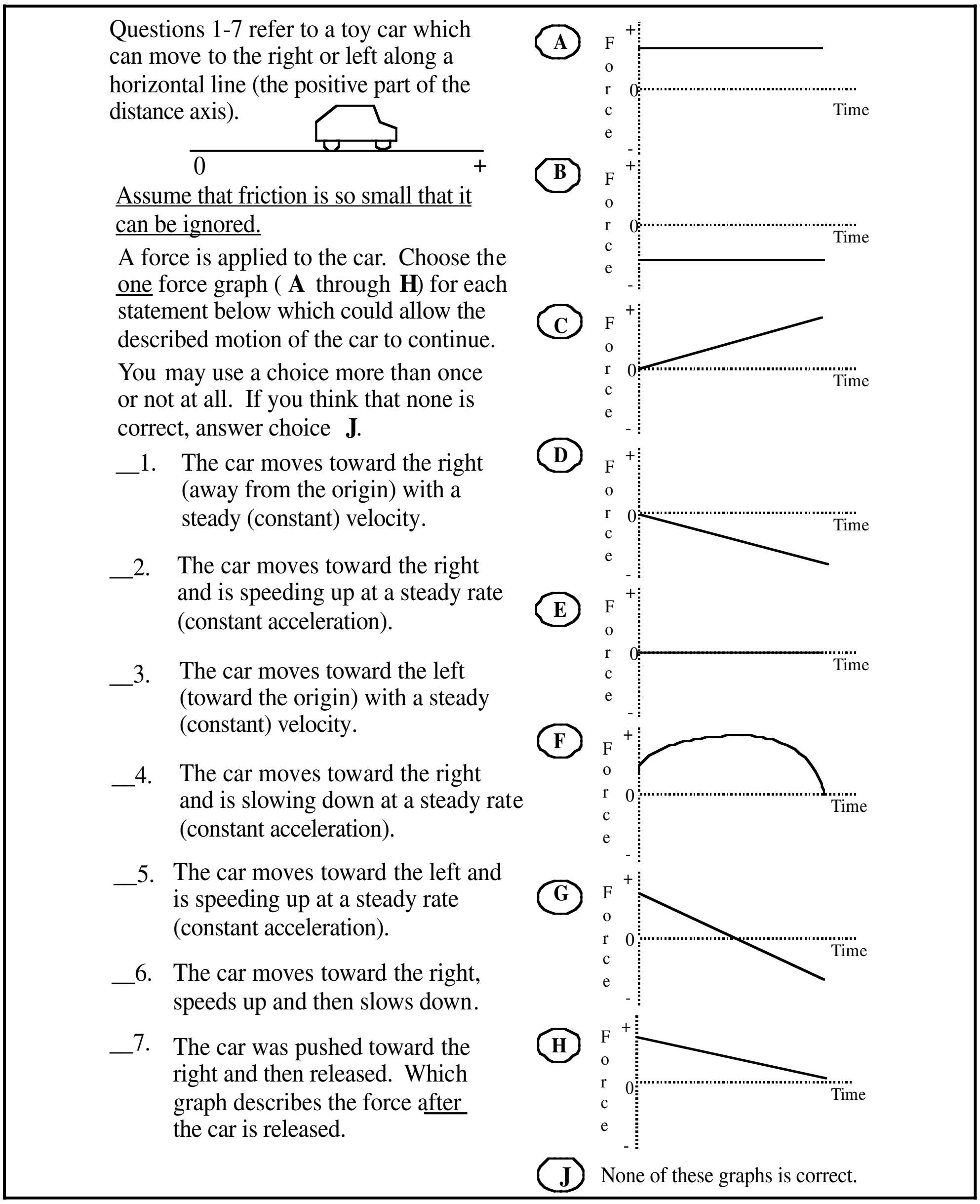
[8] Normalized learning gain is the actual improvement divided by the possible improvement, i.e., $\langle g \rangle = 100\% \times$ (post-test score − pre-test score)/(perfect score − pre-test score).



Questions 1-7 refer to a toy car which can move to the right or left along a horizontal line (the positive part of the distance axis).

<u>Assume that friction is so small that it can be ignored.</u>

A force is applied to the car. Choose the <u>one</u> force graph (**A** through **H**) for each statement below which could allow the described motion of the car to continue.

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

__1. The car moves toward the right (away from the origin) with a steady (constant) velocity.

__2. The car moves toward the right and is speeding up at a steady rate (constant acceleration).

__3. The car moves toward the left (toward the origin) with a steady (constant) velocity.

__4. The car moves toward the right and is slowing down at a steady rate (constant acceleration).

__5. The car moves toward the left and is speeding up at a steady rate (constant acceleration).

__6. The car moves toward the right, speeds up and then slows down.

__7. The car was pushed toward the right and then released. Which graph describes the force <u>after</u> the car is released.

J None of these graphs is correct.

Figure 4. A selection of Force Graph (Graphical) questions from the *Force and Motion Conceptual Evaluation* that probe student understanding of Newton's First and Second Laws using a graphical format.

results represent about an 80% normalized learning gain (see footnote 8). Because of the redundancy in the test, we are able to determine that these students are using Newton's laws of motion in a quite consistent fashion. More information on this research may be found in [5, 6, 8].

Figure 7 shows that the students in the Spring semester calculus-based course at Tufts University showed similar learning gains in dynamics after completing *RTP Mechanics*

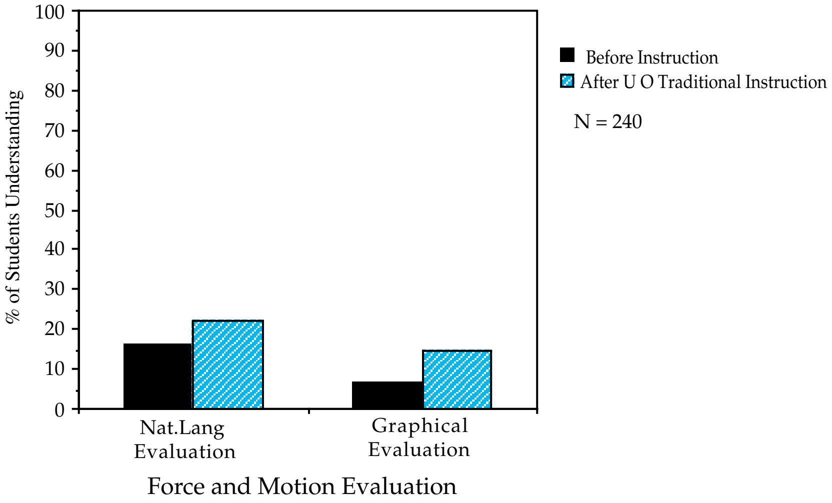


Figure 5. Student understanding of dynamics before and after traditional instruction. This graph shows the percentage of University of Oregon algebra-based introductory physics students in 1989 and 1990 who understood dynamics concepts related to Newton's first and second laws before and after traditional instruction that included lectures, problems, quizzes and examinations. The same 240 students were evaluated before and after instruction.

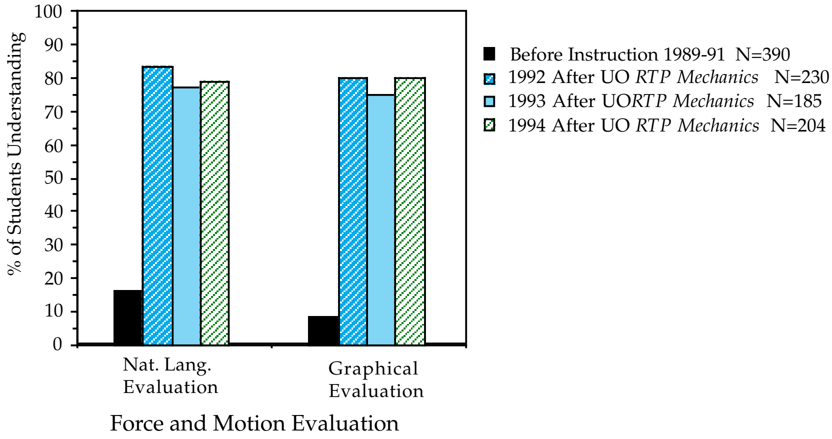


Figure 6. Effect of using *RTP Mechanics* labs on Oregon algebra-based introductory physics. The graphs show the percentage of students who understood dynamics concepts before instruction and after instruction that included completing *RTP Mechanics* lab sessions.

laboratories in 1994 and 1995. It is interesting to note that the average scores of Tufts students enrolled in the calculus-based physics course are consistently about ten percentage points higher on the pre-test than those of the University of Oregon students enrolled in the algebra–trigonometry-based physics course.

These learning gains were achieved at the development sites, Oregon and Tufts. While, as expected, the learning gains at secondary adaptor sites are not as high, still very dramatic learning gains have also been accomplished at a number of secondary sites. For example, in a research study in 1999, California Polytechnic State University (Cal Poly) in San Luis Obispo,

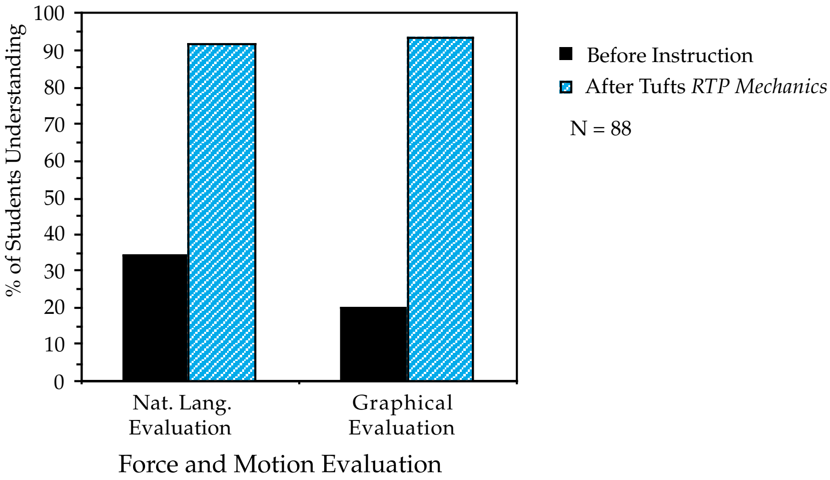


Figure 7. Effect of using *RTP Mechanics* labs in Tufts calculus-based introductory physics. The graph shows the percentage of students in the Tufts University Spring semester calculus-based introductory physics courses in 1994 and 1995 who understood dynamics concepts before instruction and after instruction that included the *RTP Mechanics* labs. The same 88 students were evaluated before and after instruction.

California, and Pacific University outside of Portland, Oregon achieved normalized gains of nearly 65% using *RTP Mechanics* [10].

The retention of Newtonian concepts by students who have completed the *RTP Mechanics* labs is also excellent. Whenever questions from the *FMCE* were asked again at Oregon and Tufts up to 6 weeks after instruction in dynamics had ended, the percentage of students answering in a Newtonian way increased by 5–10%, rather than decreasing, as is often the case. We attribute this increase to assimilation of the concepts.

Conclusions

RTP Mechanics has been used in a number of different educational settings. Like the examples just cited, many university, college and high school faculties who have used this curriculum have reported improvements in student understanding of Newton's laws. These comments are supported by our careful analysis of pre-and post-test data using the *FMCE* reported here and elsewhere [5, 6, 8]. Similar research on the effectiveness of the other *RTP* modules, also demonstrates dramatic conceptual learning gains in other topic areas. We feel that by combining the outcomes of physics educational research with microcomputer-based tools, the laboratory can be a place where students acquire both a mastery of difficult physics concepts and vital laboratory skills. These exciting outcomes with *RTP* labs have encouraged us to develop a *Suite* of active learning materials [11], including Interactive Lecture Demonstrations [12], and a physics education research-based text, Understanding Physics [13].

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We could not have developed *RTP* without the hardware and software development work of Stephen Beardslee, Lars Travers, Ronald Budworth and David Vernier. We acknowledge PASCO scientific for their development of the low-friction dynamics cart system. We also thank the faculty at the University of Oregon and Tufts University for assisting with our conceptual learning assessments and the students for participating in these assessments as well as in the testing of our laboratory activities. Both were essential for the development of the curricula. We appreciate the help of Curtis Hieggelke, Maxine Willis, Robert Morse, John Garrett and many other instructors who have used and tested our materials. This work was supported by the National Science Foundation and the US Department of Education under the Fund for Improvement of Post-Secondary Education (FIPSE) and the Secretary's Fund for Innovation.

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