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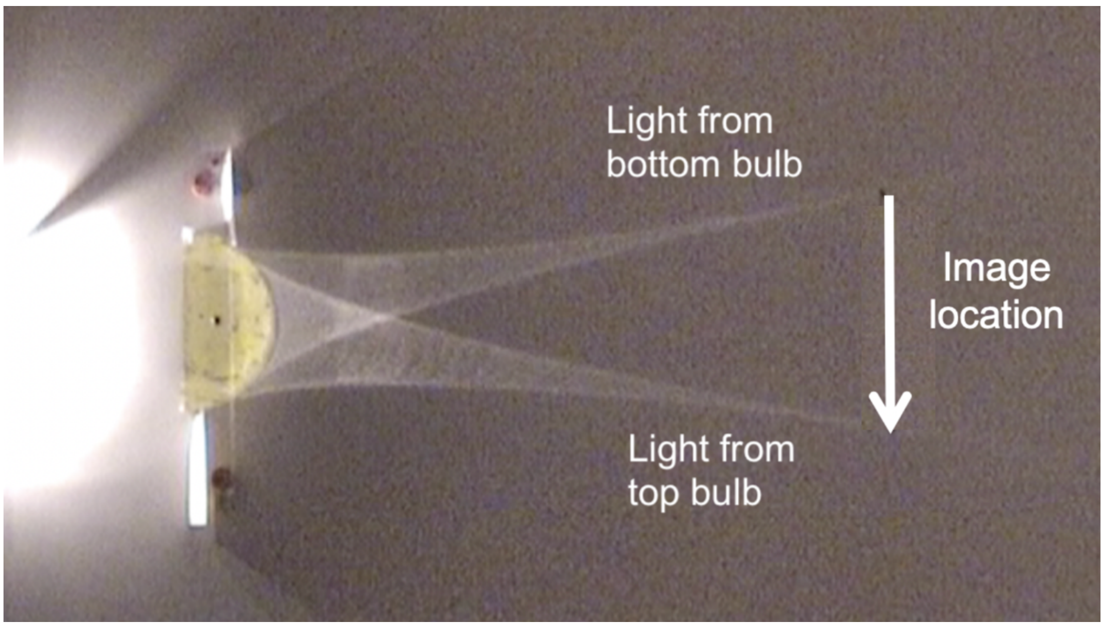

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Home Adapted Interactive Lecture Demonstrations (ILDs)

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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.

[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	Module 2: Heat and Thermodynamics
Lab 1: introduction to motion	Lab 1: introduction to heat and temperature
Lab 2: changing motion	Lab 2: energy transfer and temperature change
Lab 3: force and motion	Lab 3: heat energy transfer
Lab 4: combining forces	Lab 4: the first law of thermodynamics
Lab 5: force, mass and acceleration	Lab 5: the ideal gas law
Lab 6: gravitational forces	Lab 6: heat engines
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 3: Electric Circuits	Module 4: Light and Optics
Lab 1: batteries, bulbs and current	Lab 1: introduction to light
Lab 2: current in simple dc circuits	Lab 2: reflection and refraction of light
Lab 3: voltage in simple dc circuits and Ohm's law	Lab 3: geometrical optics: lenses
Lab 4: Kirchhoff's circuit rules	Lab 4: geometrical optics: mirrors
Lab 5: introduction to capacitors and RC circuits	Lab 5: polarized light
Lab 6: introduction to inductors and LR circuits	Lab 6: waves of light
Lab 7: introduction to ac currents and voltages	
Lab 8: introduction to ac filters and resonance	

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

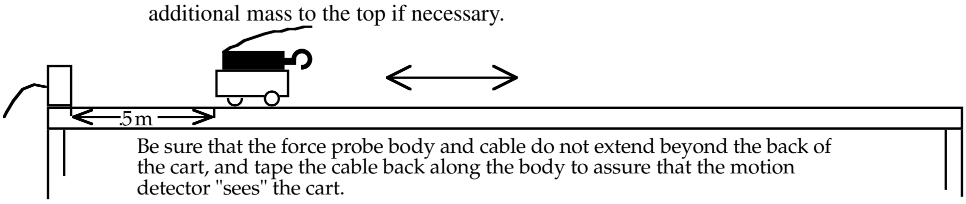
How effective is *RTP Mechanics* in helping students understand Newton's Laws of motion? To evaluate student learning in dynamics we developed the research based, multiple-choice examination called the *Force and Motion Conceptual Evaluation (FMCE)* [5, 6][7]. Responses on open-ended written questions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

[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.



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.

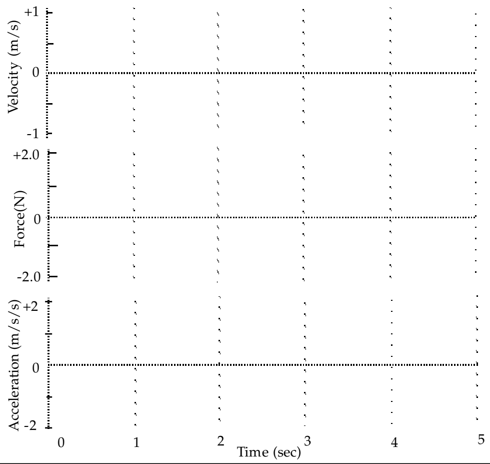


Figure 1. Excerpt from investigation 2 of *RTP Mechanics* lab 3 which illustrates that acceleration—not velocity—is proportional to force.

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.

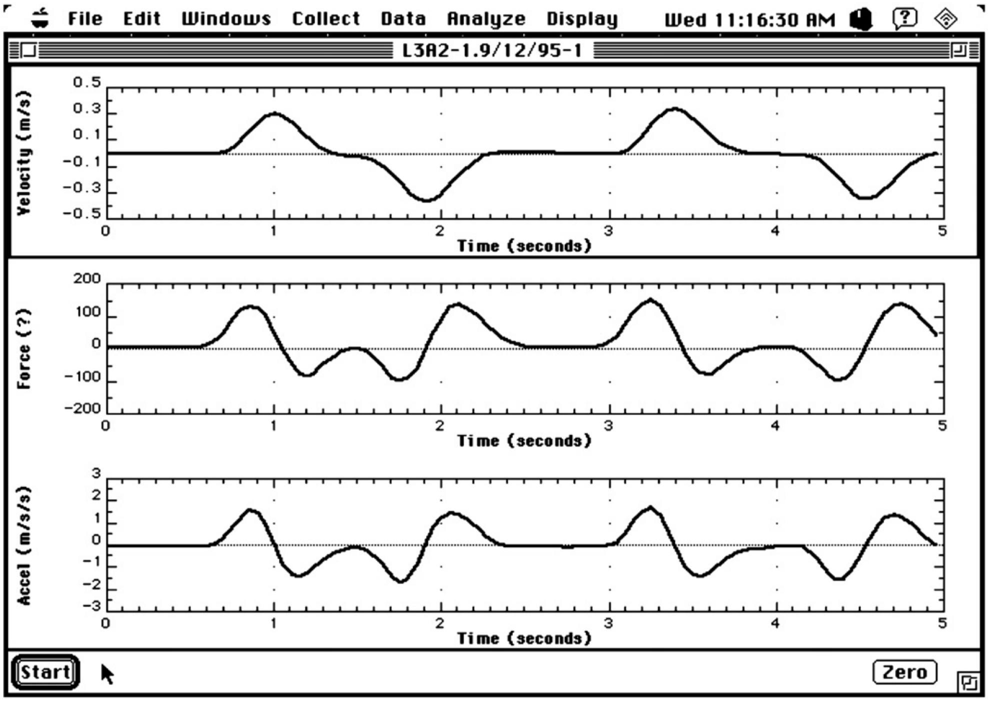


Figure 2. Velocity–, force– and acceleration–time graphs for a low-friction cart pulled away from the motion sensor beginning at about 0.6 s and then quickly stopped, then pushed back towards the motion sensor beginning at about 1.6 s and again quickly stopped, as in *RTP Mechanics* lab 3, activity 2-1.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

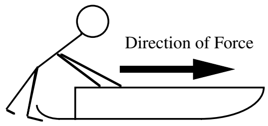
By examining pre- and post-test results we can illustrate how the *RTP* laboratory affects student understanding of dynamics. For example, two sets of questions explore the relationship between force and motion by asking about similar motions in two different ways. The first is a series of 'Force Sled' 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.

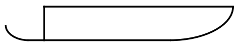
You may use a choice more than once or not at all but choose only one answer for each blank. If you think that none is correct, answer choice **J**.



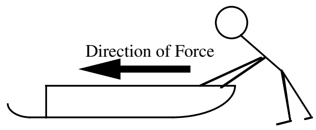
A. The force is toward the **right** and is **increasing** in strength (magnitude).

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)?

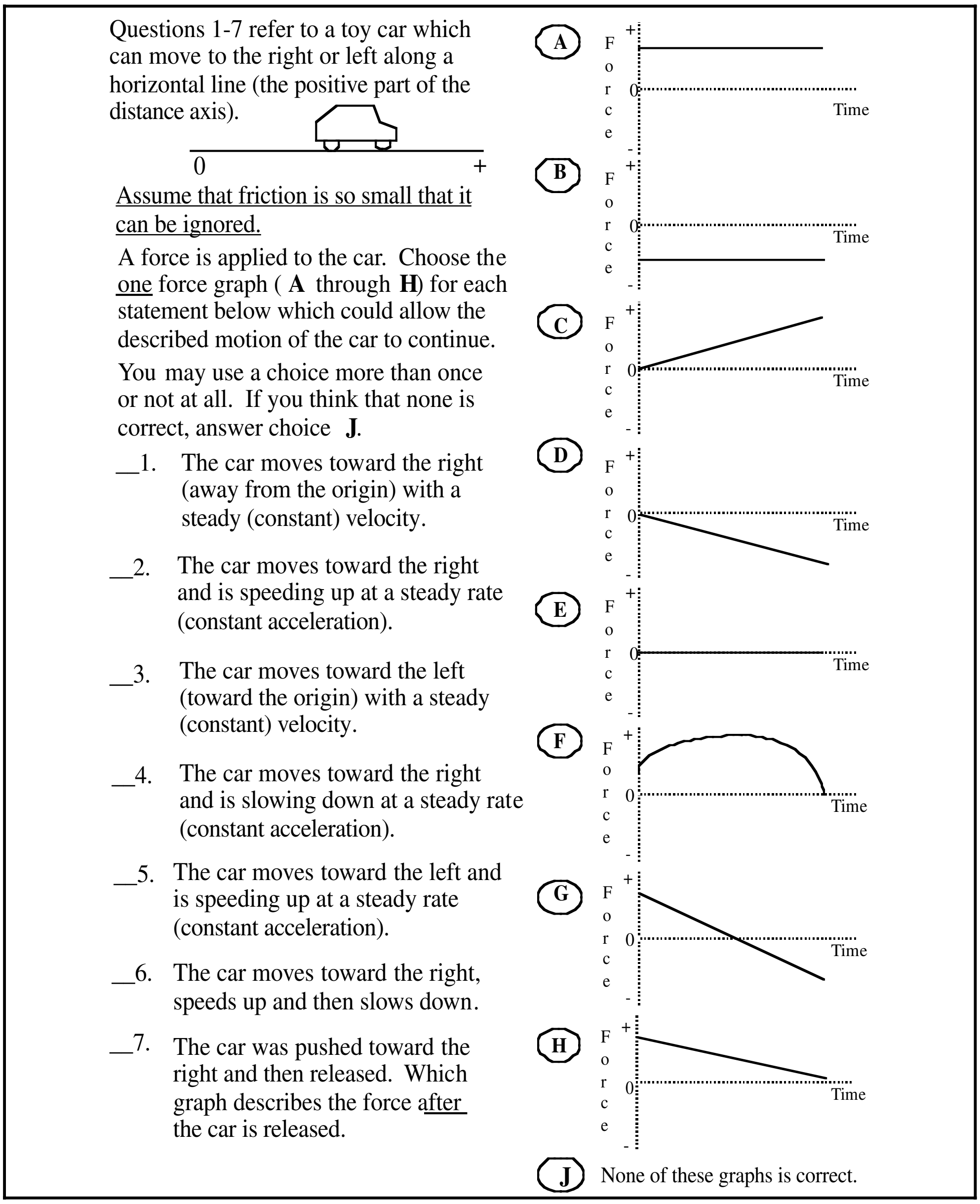
Figure 3. A selection of Force Sled (Natural Language) questions from the *Force and Motion Conceptual Evaluation* that probe student understanding of Newton's first and second laws using natural language.

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

[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).

Assume that friction is so small that it can be ignored.

A force is applied to the car. Choose the one 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 after 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*

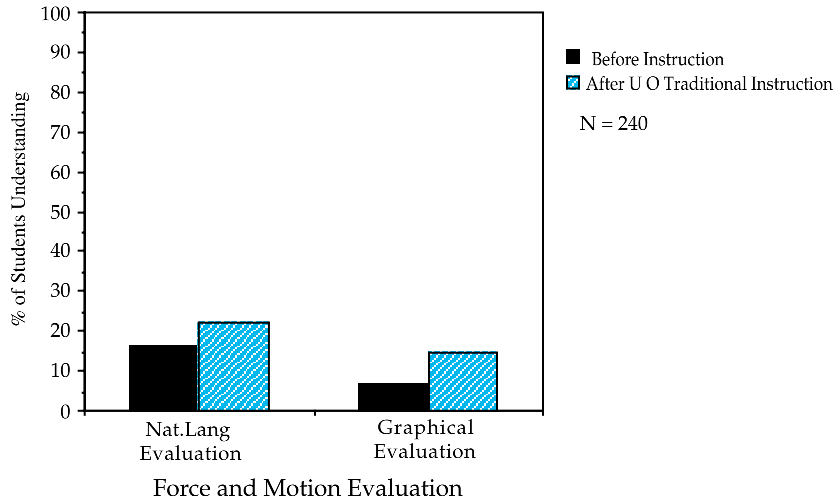


Figure 5. Student understanding of dynamics before and after traditional instruction. This graph shows the percentage of University of Oregon algebra-based introductory physics students in 1989 and 1990 who understood dynamics concepts related to Newton's first and second laws before and after traditional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

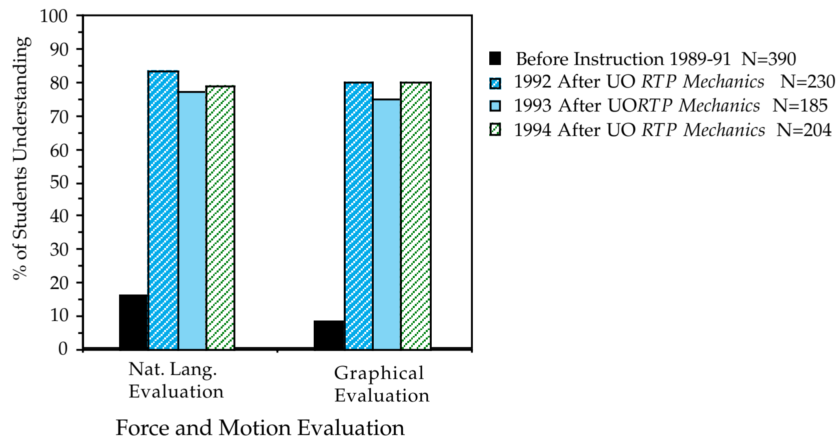


Figure 6. Effect of using *RTP Mechanics* labs on Oregon algebra-based introductory physics. The graphs show the percentage of students who understood dynamics concepts before instruction and after instruction that included completing *RTP Mechanics* lab sessions.

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,

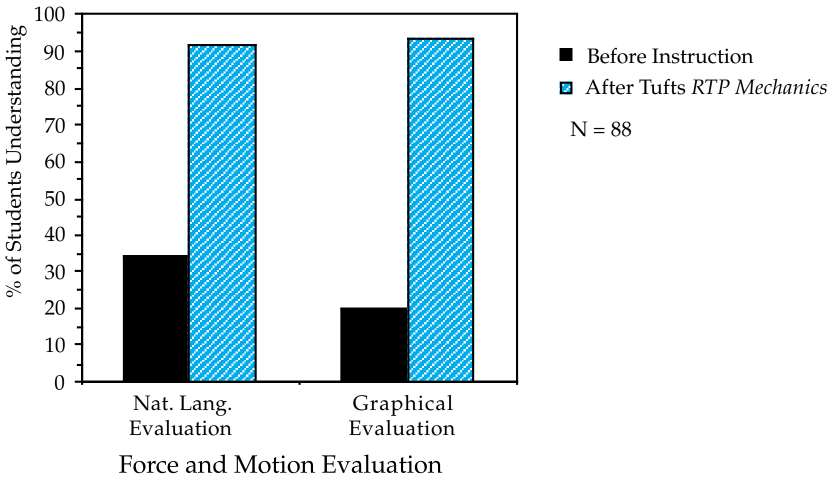


Figure 7. Effect of using *RTP Mechanics* labs in Tufts calculus-based introductory physics. The graph shows the percentage of students in the Tufts University Spring semester calculus-based introductory physics courses in 1994 and 1995 who understood dynamics concepts before instruction and after instruction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

Acknowledgments

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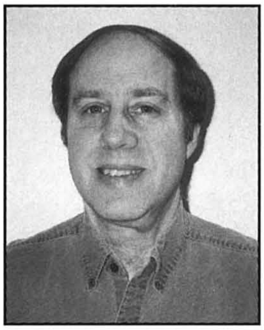
Using Interactive Lecture Demonstrations to Create an Active Learning Environment

By David R. Sokoloff and Ronald K. Thornton



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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-

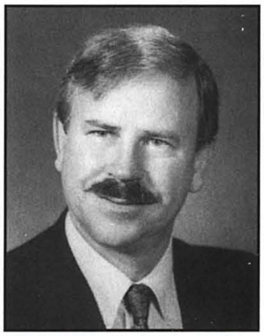

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Table I. Mechanics interactive lecture demonstration sequences.

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

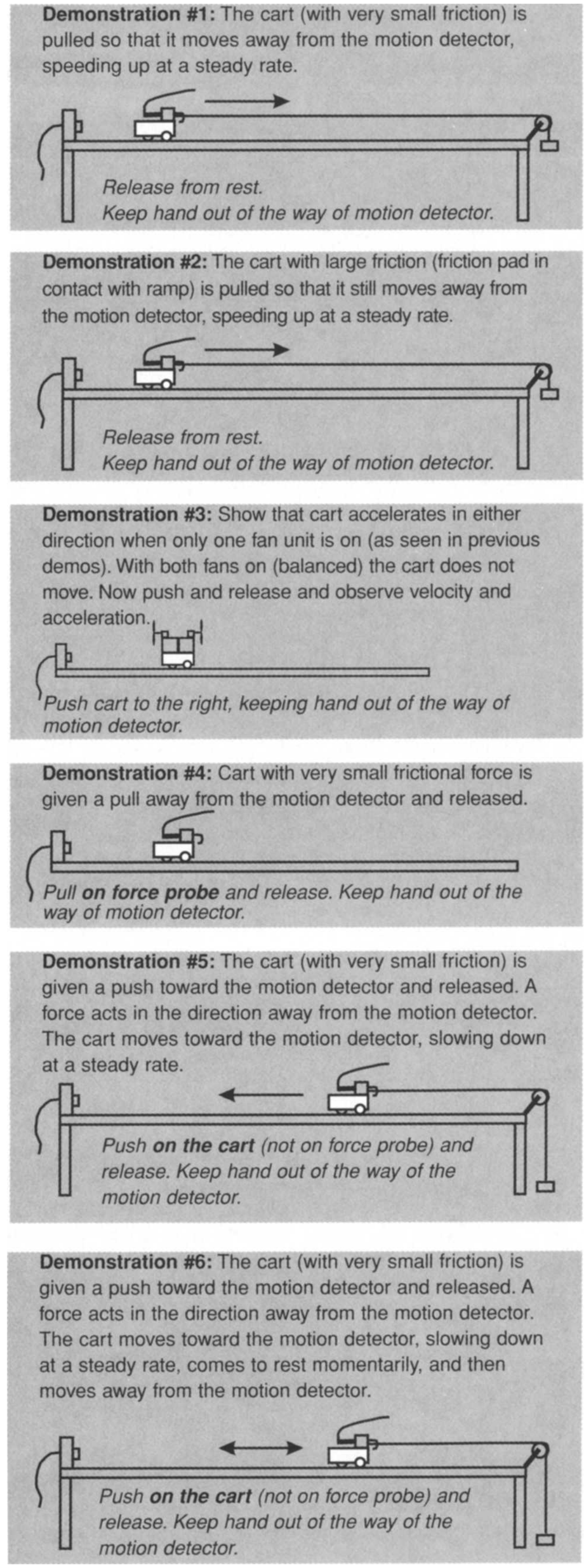
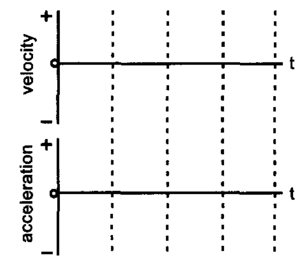


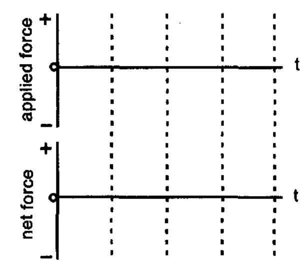
Fig. 1. ILD sequence for Newton's first and second laws. Descriptions of demonstrations taken from ILD teacher materials.

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

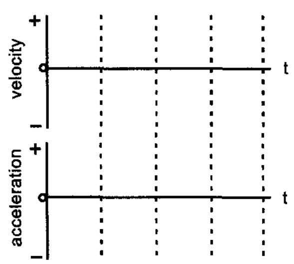
Directions:** This sheet will be collected.* ***Write your name at the top to record your presence in this class. *Follow your instructor's directions. You may write whatever you wish on the other sheet, which is the Results Sheet, and take it with you.*



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

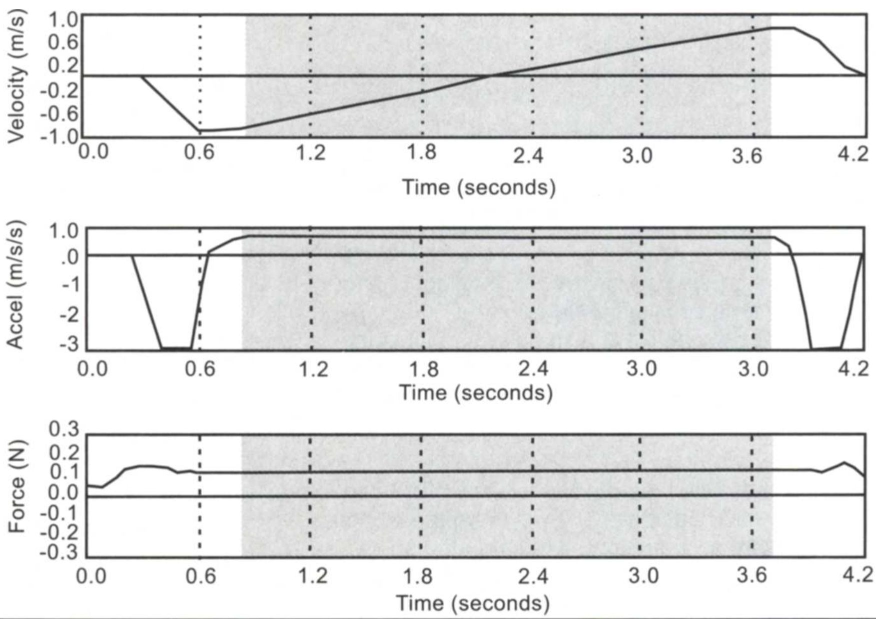


Fig. 3.* MacMotion *display of actual data (Tufts University) from Demonstration #6 in Fig. 1.

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.

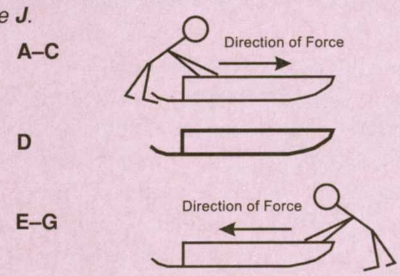
Figure 6 compares student learning of dynamics concepts in traditional instruction (where students listen to lectures, do homework problems, and take quizzes and exams) with learning in the identical course where just 80 minutes of lectures were replaced with ILD's. The baseline for traditional instruction 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

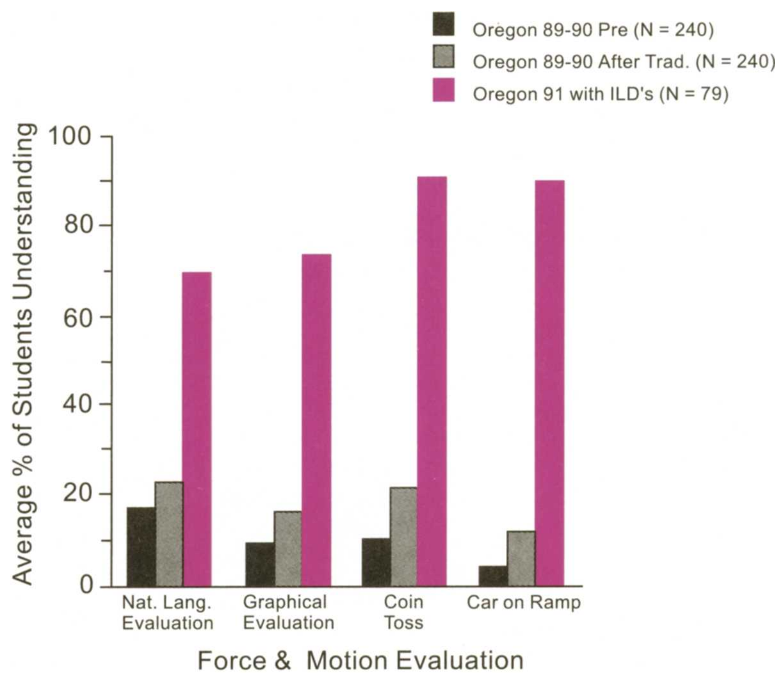


Fig. 6. Comparison of (Oregon) student learning of dynamics before and after traditional instruction (first two bars in each set) with learning when two lectures were replaced with kinematics and dynamics ILD's. Only NOLAB students are included here. See text for discussion.

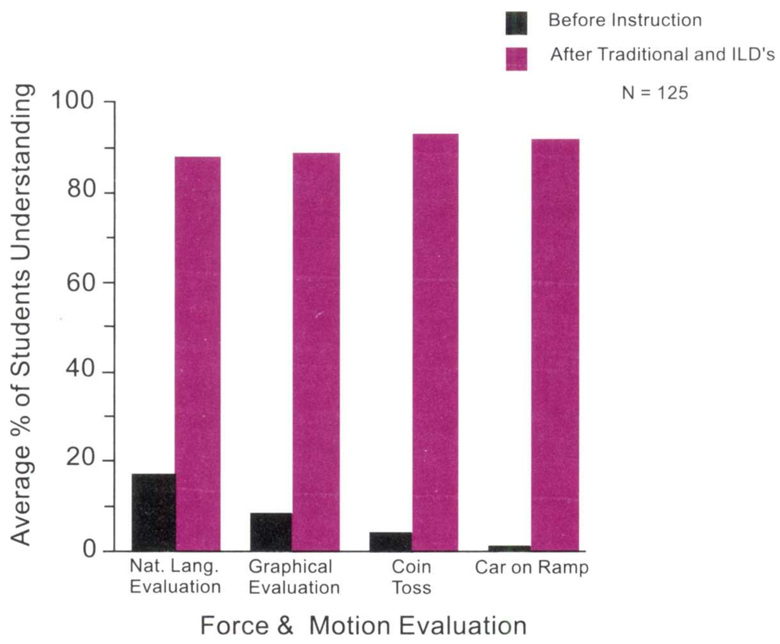


Fig. 7. Comparison of (Tufts, 1994) student learning before and after enhancing the traditional introductory course with kinematics and dynamics ILD's. These students also experienced two* Tools for Scientific Thinking *kinematic labs. See text for discussion.

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.

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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.
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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).

Adapting *RealTime Physics* for Distance Learning with the IOLab

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The IOLab is a versatile and inexpensive data acquisition device in a cart that can roll on its three wheels. It has numerous sensors for a variety of physical quantities. We adapted *RealTime Physics, Module 1: Mechanics* active learning labs for use with the IOLab. We tested these labs both on campus and with distance learners at Portland State University and Chemeketa Community College for three years, consistently obtaining significant conceptual learning gains on the Force and Motion Conceptual Evaluation (FMCE). Student attitudes towards the labs, the device, and distance learning—as measured by post-course evaluations—were generally very positive.

Fig. 1. The IOLab, an inexpensive data acquisition device in a cart that can roll on its three wheels.

Introduction

Distance higher education continues to grow[1] in spite of both flat enrollment in higher education overall[2] and scandals[3] at for-profit universities. But science fields, especially physics, have been slow to adapt to demand,[4] often based on the perceived difficulty of delivering labs effectively and safely at a distance.

The 2014 "AAPT Recommendations for the Undergraduate Physics Laboratory Curriculum"[5] include "constructing knowledge" as a desirable learning outcome. In spite of the development of online simulations and activities, it is still important for distance learning students to have an authentic laboratory experience in which they physically manipulate objects and actively use their observations to create or modify their conceptual models of the physical world. Recent advances in low-cost sensors and data analysis software make it feasible to offer physics labs in the context of an online or distance course.

But the solution to this problem requires more than technology. Recent research suggests that "traditional" lab experiences do not meaningfully impact student learning.[6,7] It should be noted, however, that this research did not include studio courses or courses implementing *RealTime Physics* (*RTP*)[8] as their lab component. In fact, it has been well documented that *RTP*—a research-validated, active learning lab curriculum—can guide students to consider and modify their conceptual understandings.[8] While *RTP* has been demonstrated to be effective in class, it cannot easily be used in distance learning due to the cost, size, and complexity of the computer-based lab equipment. For this project we proposed the combination of the inexpensive IOLab device with the *RTP* curriculum as a solution to the need for research-validated distance learning mechanics labs.

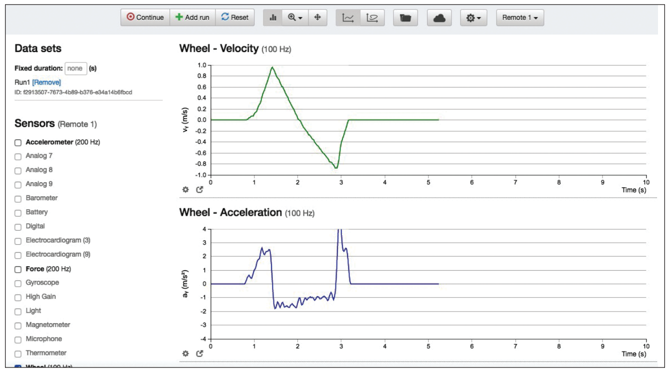

Fig. 2. Graphs of velocity vs. time and acceleration vs. time collected by the IOLab encoder for motion up and back down a smooth inclined ramp.

The IOLab and IOLab software

The low cost and versatility of the IOLab[9] make it attractive for distance learning applications. It is a versatile data acquisition device that is self-contained in a cart (see Fig. 1). Its motion on its wheels is detected by an optical encoder, allowing measurement of motion quantities. It has numerous sensors for a variety of physical quantities, including a force sensor. This makes it ideal for examining its motion under a variety of conditions, and for exploring Newton's laws of motion. Figure 2 shows graphs generated by the IOLab rolling up and back down an inclined ramp.

The basic IOLab software—that is free with the hardware—allows users to choose both the sensors to be activated and features of the graphs to be collected (such as axis limits). It also allows simple data analysis such as statistics and curve fitting. Lesson Player, a component of the IOLab software, allows these settings to be selected in advance of data collection (although students can still change them after data collection if this displays the data more clearly). With Lesson Player, instructions, questions, and answer boxes are displayed on one half of the screen while collected graphs are displayed on the other half in real time (see Fig. 3). Also, with Lesson Player, students can complete and submit their work electronically. These features are all well suited for our adaptation of *RTP* for

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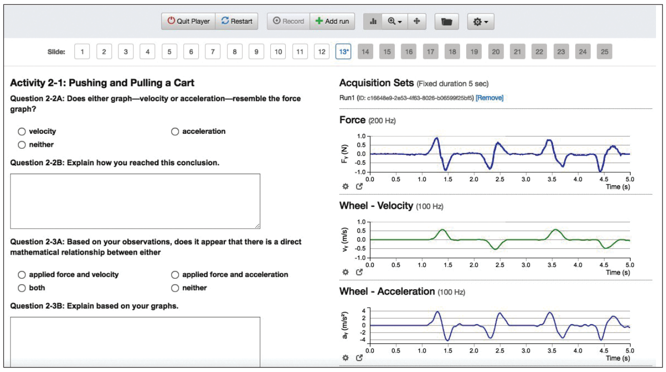

Fig. 3. An example of the appearance of a slide from Lab 4 as displayed with Lesson Player.

Table I. Active learning labs in mechanics developed for use with IOLab.

Lab 1. Introduction to IOLab
Lab 2. Introduction to Motion
Lab 3. Changing Motion
Lab 4. Force and Motion
Lab 5. More About Newton's Laws
Lab 6. Impulse and Momentum
Lab 7. Newton's Third Law and Conservation of Momentum
Lab 8. Two-Dimensional Motion
Lab 9. Work and Energy

distance learning. Other "smart carts" have become available during the timeline of this project.[10] It was not within the scope of this project to compare the capabilities of these. The PocketLab,[11] although quite capable, does not include an encoder or force sensor.

RealTime Physics pedagogy

Beginning in 1992 a set of *RTP* labs was developed with funding from the National Science Foundation. Four lab guides (modules) are currently published by John Wiley and Sons.[12] Each lab guide includes activities for use in a series of related lab sessions that span an entire quarter or semester for the lab accompanying either the calculus-based or algebra-based introductory physics course. Lab activities and homework assignments are integrated so that they build on learning that has occurred during the previous lab session and prepare students for activities in the next session. The major goals of the *RTP* curriculum are to help students: (1) acquire an understanding of a set of related physics concepts; (2) experience the physical world directly by using computer-based 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.

In order to achieve these goals, a set of design principles was developed for the laboratory guides. Lab activities (1) are sequenced and build on each other, (2) invite students to construct physical models based on their observations, (3) incorporate a learning cycle of prediction, observation, and comparison to help students to modify their common, naive conceptions, and to understand powerful general physics principles, (4) provide opportunities for students to discuss ideas and findings in small groups of two to four, (5) include a pre-lab assignment to prepare for lab and a homework assignment designed to reinforce critical concepts and skills.

The IOLab Distance Learning Laboratory project

Starting in 2015, with support from the National Science Foundation,[13] we developed a series of mechanics labs for use with the IOLab in distance learning environments. These labs are mostly based on *RTP*, as adapted for the particular characteristics of the IOLab and software.

A recent paper has documented that physics education research is typically done with students who are "better prepared mathematically and are less diverse than the overall physics student population."[14] We avoided this issue by testing the labs we developed for IOLab at Portland State University (PSU), an urban university with an 89% acceptance rate,[15] and at Chemeketa, an open-enrollment community college in the process of obtaining federal designation as an Hispanic-Serving Institution.

At PSU, all students were enrolled in a campus-based traditional lecture (either calculus or algebra-based) and experienced our labs either on campus (in a normal laboratory room) or in distance learning mode. At Chemeketa, all students were enrolled in an active learning,[17] algebra-based course. Chemeketa students were either entirely campus based or entirely in distance learning mode.[18] We loaned an IOLab to each distance learning student. While the IOLab includes a few accessories from the manufacturer such as springs and hooks, we provided an additional kit with a protractor, a bouncy ball, clay, fishing line, weights, and a few other items for an additional cost to us of about $10 per student.

Table I lists the titles of the final versions of the nine labs that we developed. (Note that Lab 8 also makes use of video analysis[19] to examine the projectile motion of a thrown ball.) Control groups at both institutions completed traditional labs: on-campus at PSU and in distance learning mode at Chemeketa with traditional lab kits.[20]

As part of the project, we tested IOLab active learning labs during five rounds at each institution.[21] Each of these rounds afforded us opportunities to observe campus-based students in class as they worked through the labs, to examine the graphs all groups collected and the lab sheets they turned in, and to assess their understanding of mechanics concepts. This was an iterative process during which we revised the labs, hardware, and software according to what we learned. Among the lessons we learned from this process are:

- The lack of bearings in the low-cost wheels of the IOLab results in significant friction. For example, the acceleration of the IOLab while rolling up an inclined ramp is noticeably different from that rolling down. (This can be seen in Fig. 2 in the change in slope of the velocity-time graph and change in acceleration on the acceleration-time graph at approximately 2 s, when the IOLab reached its highest point along the ramp.) This complicates initial learning of kinematics and Newton's laws. It is our opinion that the manufacturer should install bearings on the IOLab.

- The significant friction makes it more difficult to do the very effective *RTP* activities that directly lead to an understanding of Newton's first law. We struggled with this, and in the end had to use hanging masses to compensate for the friction.
- The level of noise in the electronic signals from the force sensor sometimes makes it difficult to see the desired experimental results.
- Because we wanted to make these labs low cost, we provided each student with *only one* IOLab. In order to incorporate the research-validated Newton's third law collision and conservation of momentum activities from *RTP* into Lab 7, we incorporated videos of two IOLabs.[22]
- Like all accelerometers, the IOLab measures proper acceleration (acceleration relative to free fall), not coordinate acceleration (acceleration with respect to the lab). This can cause conceptual difficulties for beginning students. We used accelerations calculated from the wheel encoder for this reason, and also because measurements from the encoder are pedagogically richer, since they explicitly include both velocity-time and acceleration-time graphs.
- Technical support for some distance learning students proved to be challenging, especially at Chemeketa. Students had a variety of computer operating systems and hardware, and they had a wide range of computer skills. (For example, some lacked the ability to move files from one folder to another.) At Chemeketa, we posted instructions and videos showing how to install and use the software. We also used an online discussion board where students could post questions and screen captures when they encountered problems. At PSU, we met with students in person at the beginning of the term to issue equipment and install software. Even with considerable effort to help students, a few chose to drop rather than work to overcome these issues. But the overall dropout rate was comparable to regular classes at PSU and Chemeketa.

Conceptual learning as measured with the FMCE

We measured learning of concepts related to kinematics and Newton's laws with a shortened (34-question) version of the Force and Motion Conceptual Evaluation (FMCE).[23,24] Figure 4 compares the normalized gains[25] for the most recent tests at both PSU and Chemeketa (fall 2017), after several years of refining the labs (as described above).

The randomly assigned control group at PSU[26] only completed the posttest. We calculated the normalized gain for

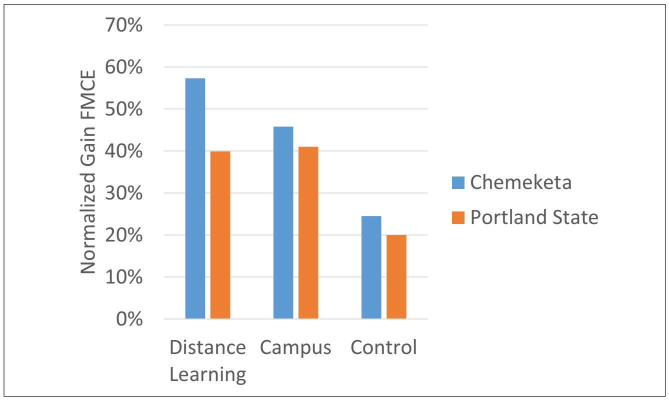

Fig. 4. Normalized learning gains on the shortened, 34-question Force and Motion Conceptual Evaluation for students at Chemeketa and PSU during fall 2017. Group sizes for Chemeketa were Distance *N*=30, Campus *N*=26, Control *N*=25. For PSU, Distance *N*=41, Campus *N*=33, Control *N*=69.

this control group assuming that their pretest score was the same as the average of the PSU IOLab group. (From previous rounds, we knew that the pretest scores do not differ substantially for the various groups at PSU.) The Chemeketa controls completed both the pre- and posttest, and their normalized gains were calculated directly.

The conceptual learning gains by the IOLab groups are consistently significantly better than the control groups that did traditional labs. Note that all students at PSU were experiencing traditional lectures from several different lecturers whom the students selected randomly. Therefore, the higher learning gains for the IOLab groups can be attributed to their IOLab experience. The distance learning students at Chemeketa experienced "lecture" material enhanced by active learning strategies,[15] which probably accounts for their somewhat higher overall learning gains. While these results are not as good as those achieved with *RTP*,[8] we conclude that our adaptation of *RTP* for the IOLab consistently and measurably improves student conceptual understanding for both distance learning and campus-based students.

Evaluation of student attitudes

The students experiencing the labs, IOLab device, and IOLab software had generally favorable attitudes towards their experience, as indicated by their responses on end-of-term lab course evaluations. For example, Table II shows the average response (5 = strongly agree, . . . 1 = strongly disagree) to a number of statements describing the experience of the PSU students who did the labs in distance learning mode during fall 2017. The ratings of statements 1 and 2 indicate that the students were comfortable carrying out the experiments on their own, at home, while statements 4-7 indicate a positive feeling about the learning environment established by these labs. The results on statement 3 (5 = learned much more, . . . 1 = learned a lot less) indicate a generally positive perception of the learning experience with the IOLabs.

Although we did not set out to change attitudes towards experimental physics, we did check if any changes occurred. We had students respond to portions of the E-CLASS[27] both pre and post in fall term 2017. We did not find any change in

Table II. Average response on end-of-term evaluations by distance students at PSU, fall 2017, *N*=41.

1	Knowing there are 10s of very short YouTube videos online, explaining some of the more confusing parts of using IOLab and software, I could have done these labs at home.	4.4
2	Compare your perception of learning using this style of lab instructions to the lab instructions you have used in other labs.	3.6
3	These labs helped me with my conceptual understanding of physics.	4.2
4	I have gained a greater insight into the nature of the physical world.	4.1
5	I have learned useful concepts from the laboratory course.	4.2
6	The laboratory course added to my understanding of the lectures.	3.9

student strategies, habits of mind, or attitudes towards experimental physics based on this metric.[28]

Implementation observations from the instructors

From the instructor's perspective there are a number of advantages to the IOLab-based experiments:

- There were few conceptual questions from distance learning students. When they contacted us, it usually concerned a technical issue, not difficulty in understanding the physics.
- The labs do a good job of connecting real-world experiences to mathematical representations.
- Grading is easier compared to standard labs. There is only one file for each lab, and all students submit essentially the same format file.

For campus-based labs:

- It is easier to demonstrate concepts to students with the IOLab equipment.
- Set up and tear down is much easier compared with most standard, traditional labs.
- There is less time needed to explain how the lab equipment works and, therefore, more time for student work and discussion.
- If students miss a class because of illness, etc., they can borrow an IOLab to make it up. (Of course, providing accommodations for excused absences is one big benefit of distance learning classes, and in several instances made it possible for students to take the course.)

Conclusions

We have established that research-validated introductory physics labs can be delivered effectively in distance learning mode at low cost using IOLab. While the goals of the introductory lab can certainly be debated, they should be both explicit and measurable. We consider conceptual learning in lab to be important and achievable, and we urge the physics education community to embrace active learning, research-validated labs. The labs we developed for use with the IOLab are a viable, inexpensive option.

Acknowledgments

We would like to thank Dr. Mats Selen and his colleagues at the University of Illinois and Dr. Geoffroy Piroux at B12 Consulting for development of the IOLab and software. We also thank Dr. Selen for providing IOLabs for our pilot studies, and for listening to the many suggestions we made for improving the IOLab software, and Dr. Piroux for rapidly implementing most of these suggestions. We thank Dr. Kathleen Harper for her guidance as our evaluator, the NSF for financial support of our work, John Wiley and Sons for their permission to adapt *RTP*, and MacMillan, the manufacturer and distributor of the IOLab. We also thank Chemeketa students Paul Ivanov, Nicholas Jones, and Benjamin Steele and PSU teaching assistants Mike DeArmond and Caitlin Kepple for their contributions to this project.

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25. Normalized gain <*g*> is defined by <*g*> = 100% x [(Post.score-Pre.score)]/[(Max. possible score-Pre.score)].
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Active Learning Strategies for Introductory Light and Optics

This colorful graphic signals that this contribution is a featured part of "The Art, Craft, and Science of Physics Teaching" special collection. See the editorial in the October 2015 issue of *TPT* for more details.

David R. Sokoloff, University of Oregon, Eugene, OR

There is considerable evidence that traditional approaches are ineffective in teaching physics concepts, including light and optics concepts.[1-3] A major focus of the work of the Activity Based Physics Group[4] has been on the development of active learning curricula like RealTime Physics (RTP) labs[2,5] and Interactive Lecture Demonstrations (ILDs).[6,7] Among the characteristics of these curricula are: (1) use of a learning cycle in which students are challenged to compare predictions—discussed with their peers in small groups—to observations of the physical world, (2) use of guided hands-on work to construct basic concepts from observations, and (3) use of computer-based tools. It has been possible to change the lecture and laboratory learning environments at a large number of universities, colleges, and high schools without changing the structure of the introductory course. For example, in the United States, nearly 200 physics departments have adopted RTP,[8] and many others use pre-publication, open-source versions or have adopted the RTP approach to develop their own labs. Examples from RTP and ILDs (including optics magic tricks) are described in this paper.

RealTime Physics: Active Learning Labs (RTP)

RealTime Physics is a series of lab modules that makes significant use of computer-based tools to help students develop important physics concepts while acquiring vital laboratory skills.[2,5] Besides data collection and analysis, computers are used for basic mathematical modeling, video analysis, and some simulations. RTP labs use a learning cycle of prediction, observation, and comparison. They incorporate a guided discovery approach in which students carry out structured, sequenced experiments in small groups. Students are guided by PER-motivated questions designed to help them reach conclusions from clearly displayed observations of the physical world. RTP labs have been shown to enhance student learning of physics concepts.[1,2] There are four RTP modules—Module 1: Mechanics, Module 2: Heat and Thermodynamics, Module 3: Electricity and Magnetism, and Module 4: Light and Optics.[5] Each lab includes a pre-lab preparation sheet to help students prepare and homework designed to reinforce critical concepts and skills. A complete teacher's guide is available online for each module. Here are two examples of activities from RTP Module 4.[9]

- ***Polarized light:*** As an example of an activity that makes use of technology, Fig. 1 shows the apparatus used to examine polarized light in Lab 5. It consists of an analyzer fabricated from a Polaroid disc mounted on a precision rotary motion sensor[10] with a light sensor[11] mounted behind it. Using a flashlight with a Polaroid sheet mounted on its lens as the light source, the graph in Fig. 2 traces out as the analyzer is rotated. Figure 2 also shows a graph of $A \cos^2 \theta$ that has been adjusted both in amplitude and phase to model the collected data very well (evidence for Malus' law).

- ***Image formation:*** Many of the most innovative RTP optics activities are low-tech. This activity from Lab 3 is inspired

Fig. 1. Apparatus used to analyze polarized light in RealTime Physics Module 4, Lab 5.

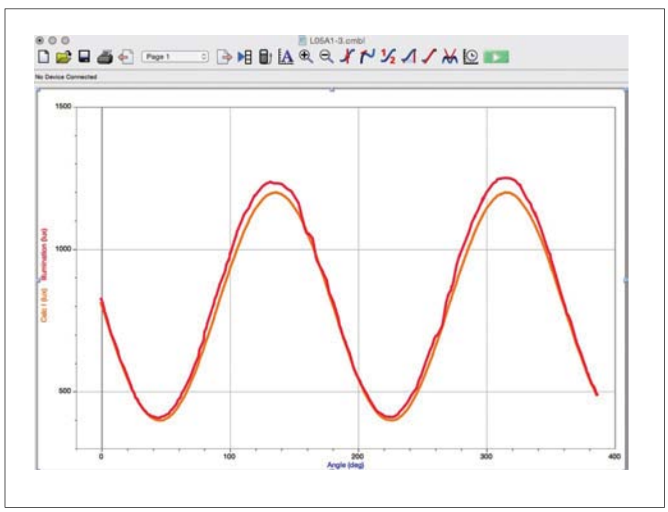

Fig. 2. Graphs of the data collected with the apparatus in Fig. 1, and of an $A \cos^2 \theta$ model for intensity vs angle.

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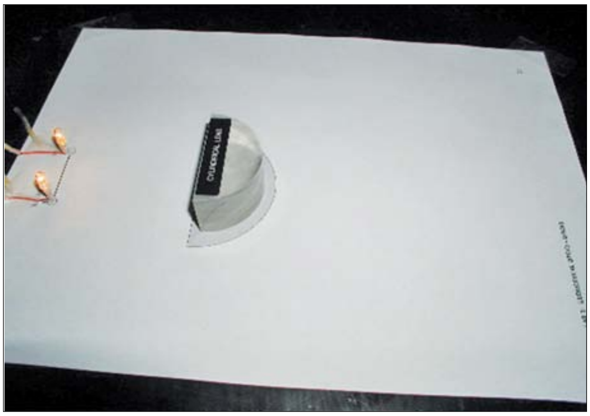


Fig. 3. Setup of two miniature light bulbs and a cylindrical lens, used to explore image formation.

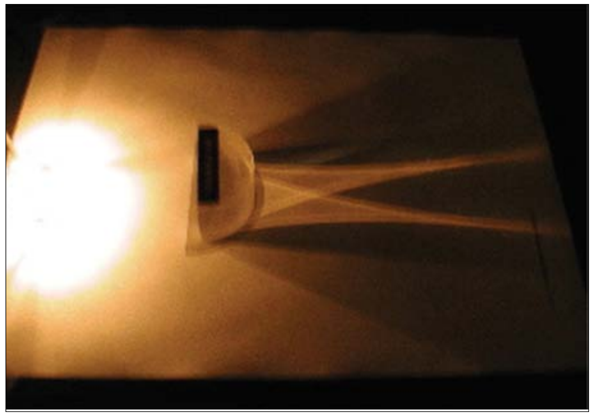


Fig. 4. The same setup as in Fig. 3 with the two bulbs illuminated.

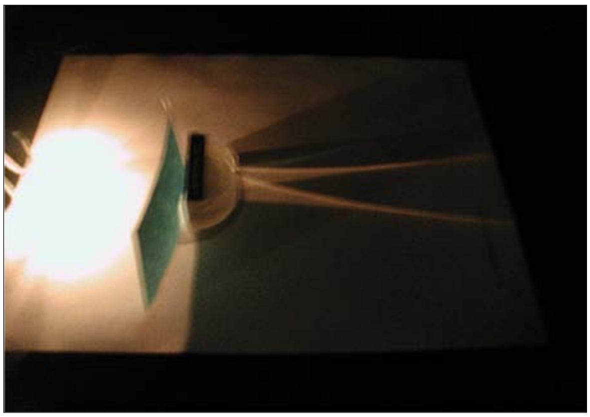


Fig. 5. The same setup as in Fig. 4, but with half of the lens blocked by a card.

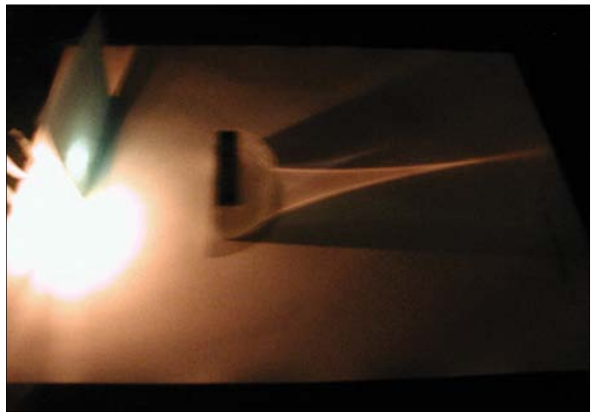


Fig. 6. The same setup as in Fig. 4, but with one of the bulbs blocked with a card.

by the research of Goldberg et al.,[3] which shows that after traditional instruction, most students have little understanding of the function of a lens in forming an image. Focusing on two or three special rays causes students to fail to recognize the infinite number of rays (light flux[12]) emanating from each point on the object and focused to a corresponding point on the image. In this activity, students use miniature light bulbs (or LEDs) as two point sources on the object, and a cylindrical lens[13] to view the situation clearly in two dimensions.

Figure 3 shows the setup, and Fig. 4 shows what appears when both bulbs are illuminated. The two image points can be recognized as the points to which the light flux leaving each of the bulb filaments (viewed in two dimensions) is focused. Next, students are asked to predict what will happen when various changes are made. For example, what happens if half of the lens is blocked with a card? (Research shows that the majority of students predict that either half or the entire image disappears.[3]) Figure 5 shows that light from both point sources is still focused to the same two image points, but now only half as much light. Therefore, the image is the same in every way as in Fig. 4, except that it is dimmer. In contrast, Fig. 6 shows what happens when half of the object is blocked by the card. Figure 7 shows an excerpt from the lab. In other activities, students are asked to explore what happens when the lens is moved further away or closer to the object, and when the lens is removed.

Prediction 1-3: Suppose that you covered half of the side of the lens facing the arrow with a card, i.e., covered the top half of the lens as seen in the diagram above. How would the image be changed? Would the whole image of the arrow still be formed?

10. Move the lens back on the outline. Block the top half of the lens (as seen in the diagram above) with a card.

Question 1-9: Carefully describe what happens to the image. Explain your observations based on what happens to rays from each of the bulbs that hit the unblocked half of the lens.

Fig. 7. Excerpt from RealTime Physics Module 4, Lab 3 showing the activity illustrated in Fig. 5.

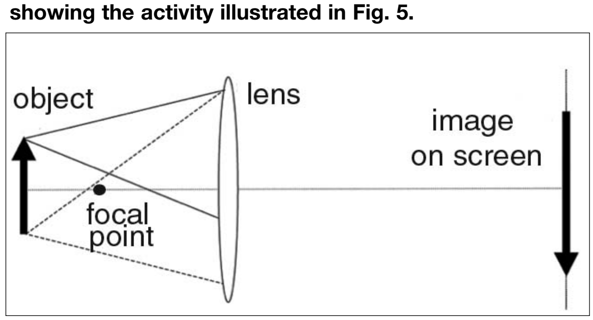
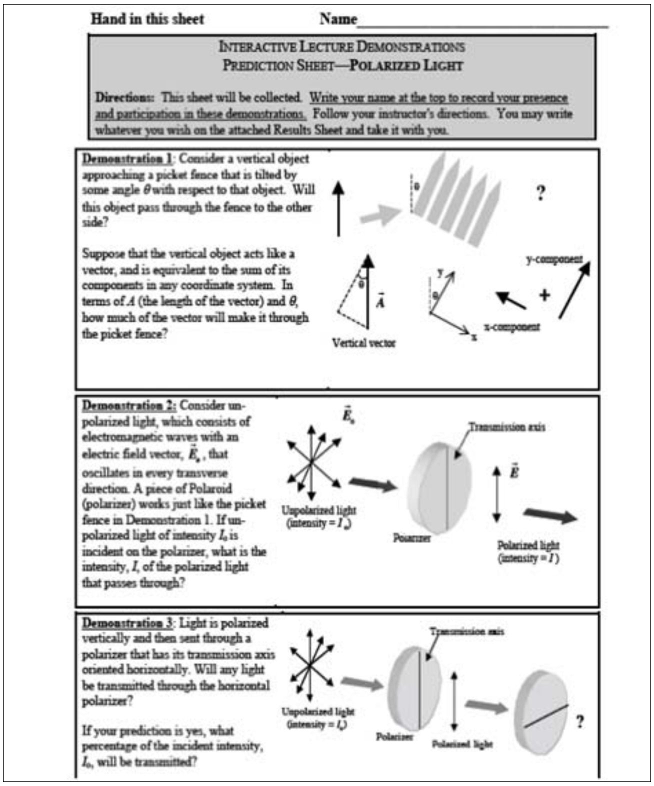


Fig. 8. Question from the "Light and Optics Conceptual Evaluation" in which students are asked to continue the four rays to illustrate how the image is formed on the screen.


Hand in this sheet Name____________

INTERACTIVE LECTURE DEMONSTRATIONS
PREDICTION SHEET—POLARIZED LIGHT

Directions: This sheet will be collected. Write your name at the top to record your presence and participation in these demonstrations. Follow your instructor's directions. You may write whatever you wish on the attached Results Sheet and take it with you.

Demonstration 1: Consider a vertical object approaching a picket fence that is tilted by some angle θ with respect to that object. Will this object pass through the fence to the other side?

Suppose that the vertical object acts like a vector, and is equivalent to the sum of its components in any coordinate system. In terms of A (the length of the vector) and θ, how much of the vector will make it through the picket fence?

Demonstration 2: Consider unpolarized light, which consists of electromagnetic waves with an electric field vector, $\vec{E}_o$, that oscillates in every transverse direction. A piece of Polaroid (polarizer) works just like the picket fence in Demonstration 1. If unpolarized light of intensity I_o is incident on the polarizer, what is the intensity, I, of the polarized light that passes through?

Demonstration 3: Light is polarized vertically and then sent through a polarizer that has its transmission axis oriented horizontally. Will any light be transmitted through the horizontal polarizer?

If your prediction is yes, what percentage of the incident intensity, I_o, will be transmitted?

Fig. 9. Excerpt from the Polarized Light ILD Prediction Sheet.

Do students learn optics concepts from these RTP image formation activities? Students in the algebra-trigonometry-based general physics course at the University of Oregon (predominantly biology, pre-health, and architecture majors) had only a 20% normalized learning gain on the six image formation questions of the PER-based "Light and Optics Conceptual Evaluation" (LOCE) after completing all traditional instruction on optics. After this lab, their learning gain from the pre-test was 90%. In addition, the last question on the LOCE shows the real image of an arrow formed by a lens, with two (non-principal) rays from the bottom of the arrow and two (non-principal) rays from the top of the arrow drawn incident on the lens (see Fig. 8). Students are asked to continue these four rays through the lens to illustrate how the image is formed by the lens. This task is easy if one understands the function of a perfect lens. After traditional instruction, only 33% of the students were able to draw these rays correctly, but after experiencing the RTP image formation activities, 76% could do so.[14]

Interactive Lecture Demonstrations (ILDs)

Since the majority of introductory physics students spend most of their time in a lecture—often a large one—creating an active learning environment in lecture is an important pedagogical challenge. Interactive Lecture Demonstrations (ILDs)[6,7] address this need. Real physics demonstrations are described and shown to students (without displaying the results). The students then make individual predictions about the outcomes on a Prediction Sheet, and collaborate with fellow students by discussing their predictions in small groups. Volunteers present their predictions to the entire class. Next the class observes the results of the live demonstrations (often with data displayed using computer-based tools). Students compare the results with their predictions, and volunteers attempt to explain the observed phenomena to the entire class. The eight-step ILD procedure has been described elsewhere.[6,7] ILDs have been demonstrated to enhance student learning of physics concepts.[1,7] Complete materials—including student sheets and teacher's guides—are available for most introductory physics topics.[6] The ILDs on the two RTP topics discussed in the "RealTime Physics" section will be described very briefly here.

- ***Polarized light ILDs:*** Figure 9 shows excerpts from the Prediction Sheet. The demonstrations can be carried out easily with sheets of Polaroid and a projector, or can also be done more quantitatively using the apparatus shown in Fig. 1.

- ***Image formation with lenses ILDs:*** When done as ILDs, two flashlight bulbs are used as the point sources of light, and a large cylindrical lens[15,16] is used to make the demonstration visible to the entire class. The normalized gain on the LOCE image formation questions for students experiencing just one hour of these ILDs (but not the RTP lab) is 80%![14] This sequence of ILDs has also been presented at Oregon using clickers (personal response systems) for students to record their predictions. Learning gains, while not quite as large, were still substantial. These results will be reported elsewhere.

Optics magic tricks

A number of years ago, the author compiled a set of 12 simple optics demonstrations presented as magic tricks to use in Saturday morning magic shows at the hands-on science center that he directed (the Eugene, OR, version of the Exploratorium). He has since used them in general physics classes at the University of Oregon. Students are actively engaged in the learning process by discussing questions in small groups. The first four tricks on geometrical optics are (1) Reappearing Test Tube (reflection from a transparent object and index of refraction—details presented below), (2) Candle Burning Under Water (properties of the image formed by a plane mirror), (3) Coal to Silver (total internal reflection), and (4) Falling Laser Beam (total internal reflection and fiber optics). Complete information is available from the author.

Reappearing Test Tube

A test tube is held up in the air for all to see, then placed in an envelope and smashed. The demonstrator then pours the glass pieces into a transparent container filled with a "magic" fluid. A magic wand is waved over the container, and, after the demonstrator says the magic word (e.g., "PHYSICS"), a whole test tube is pulled from the container. For dramatic effect—and to elicit a good laugh—it is fun to then pull a second whole test tube from the magic fluid! Figure 10

Fig. 10. Container of "magic" fluid and pieces of shattered glass test tube.

shows the container with the "magic" fluid, and Fig. 11 shows a whole test tube being removed.

Figure 12 shows the questions used for small group discussions about this magic trick. The use of small group discussions, with these guiding questions, makes the pedagogy similar to ILDs, but without the prediction step. As with ILDs, lively small group discussions erupt in lecture, suggesting that students are engaged by this strategy. To help students in thinking about these questions, the demonstrator also holds a clean test tube in the air and then submerges it under water in a separate, identical transparent container. For one more dramatic effect after the class discussion, the demonstrator can slowly submerge another dry test tube open side up so that the oil flows over the rim. It appears to disappear from the bottom up—seemingly in a flash!

• Preparation and materials: The easiest way to do this trick is to use vegetable oil as the magic fluid and a Pyrex© glass test tube. Any vegetable oil has nearly the same index of refraction as Pyrex©, so that the whole test tube (or two test tubes) placed in the container before class cannot be seen by the students. (In fact, the author has "performed" this trick all around the world [see next section] and the local vegetable oil provided has always worked—unless it was opaque at room temperature!) Alternatively, a mixture of light and heavy mineral oils can be used to match the index of any common glass.

• Explanation: Transparent objects only reflect and refract light when they are in a medium with a different index of refraction. Since the "magic" fluid has the same index as the tube, no light is reflected to the students' eyes by the submerged tube. However, students can see the tube in air or water because these have different indexes than glass. When volunteers share their small group's discussions with the whole class, they are always able to explain that the "optical properties" of the glass are the same as the "magic" fluid, even if they do not yet know the meaning of "index of refraction." For students who have studied index of refraction, the observations in this trick help support the $(n_1 - n_2)^2$ dependence of the reflectance at the plane interface between two transparent media.

Fig. 11. Whole test tube removed from the "magic" fluid after the magic wand is waved over it and the magic word is recited.

Discussion Questions for Optics *Magic: Reappearing Test Tube*

1. How do you think that the test tube was made to reappear?
2. Why can you see a test tube in air or in water, but not in the magic fluid? What is special about the magic fluid?
3. What property of transparent media determines whether reflection takes place at the boundary between them? What has to be true about this property for the two materials in order for reflection to take place?
4. What about the light that is transmitted through the test tube? How is it affected when the test tube is in the magic fluid and when the test tube is in air?

Fig. 12. Questions used for small group discussions about the Reappearing Test Tube magic trick.

Active Learning in Optics and Photonics (ALOP)

This paper has presented some innovative uses of active learning in teaching optics in the introductory physics course. RTP and ILDs are now used extensively in classes in the United States to enhance student learning of physics concepts.

Since 2004, active learning pedagogy has also been the basis for a series of UNESCO Active Learning in Optics and Photonics workshops for physics instructors in developing countries.[17,18] These ALOP workshops (1) are designed for secondary and first-year college faculty, (2) include teacher updating and introduction to active learning, (3) are locally organized, (4) use simple, inexpensive apparatus available locally or easily fabricated, (5) are presented by an international team of volunteer educators, (6) include the LOCE to measure student learning, (7) provide complete teacher's guides, and (8) distribute equipment sets to facilitate local implementation. Figure 13 shows some of the low-cost apparatus used in these workshops, while Fig. 14 shows a large low-cost cylindrical lens—a plastic food storage container filled with water.

ALOP's intensive workshops share active learning pedagogy like that found in RTP and ILDs. Some ALOP activities

Fig. 13. Low-cost equipment for ALOP: lasers, diffraction gratings from discarded CDs, slits scratched into coated mirrors, cellophane color filters, and spectrometer from a diffraction slide.

Fig. 14. Low-cost cylindrical lens—clear plastic food container filled with water.

can be introduced in either format. The *ALOP Training Manual* [14] includes six modules: (1) Introduction to Geometrical Optics, (2) Lenses and Optics of the Eye, (3) Interference and Diffraction, (4) Atmospheric Optics, (5) Optical Data Transmission, and (6) Wavelength Division Multiplexing. Each of these includes practical applications designed to intrigue students, helping them to understand their everyday world and become aware of career opportunities based on the principles they are learning. To date, 27 ALOP workshops have been presented in Africa, Asia, Latin America, and Eastern Europe. The ALOP team was awarded the 2011 SPIE Educator Award "in recognition of the team's achievements in bringing basic optics and photonics training to teachers in the developing world."[19] For more details on ALOP, see Refs. 14, 17, and 18.

Acknowledgments

The author thanks Priscilla Laws, Ronald Thornton, and the other members of the Activity Based Physics Group[4] for an extraordinary 28-year collaboration including RTP and ILDs. These developments would have been impossible without generous support from the National Science Foundation and U.S. Department of Education, F.I.P.S.E. He also thanks the ALOP team and UNESCO for their collaboration on an awe-inspiring adventure in active learning.

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14. *Active Learning in Optics and Photonics Training Manual*, edited by David R. Sokoloff (UNESCO, Paris, 2006).
15. See, for example, the acrylic lens from a Blackboard Optics set, http://sciencekit.com/blackboard-optics-kit/p/IG0023843/.
16. A clear plastic food storage container filled with water can be used as a cheaper alternative. See Fig. 14.
17. http://www.unesco.org/new/en/natural-sciences/special-themes/science-education/basic-sciences/physics/active-learning-in-optics-and-photonics-alop/.
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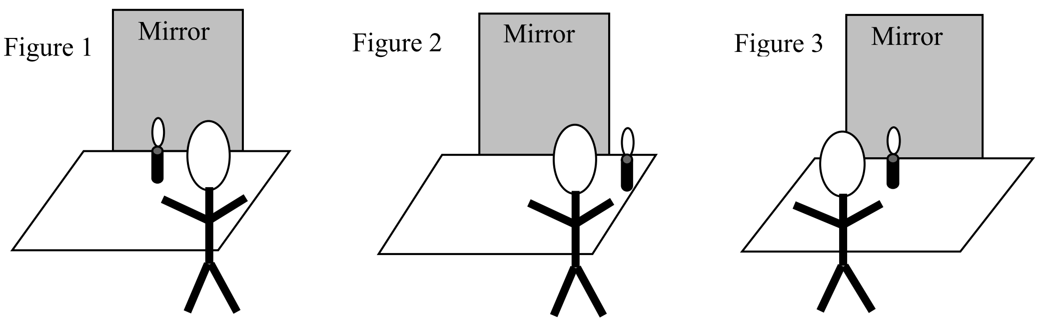
Name____Class________________________

Light and Optics Conceptual Evaluation

DIRECTIONS: Answer questions 1-50 on the answer sheet by writing in the letter corresponding to the best choice. Also include brief written answers for Questions 28, 30, 31, and 34, and sketch your answer for Question 51, all on the answer sheet.

Questions 1-5 refer to the three figures below of a candle on a table in front of a plane (flat) mirror.



1. In Figure 1, a person is standing in front of the table looking into the mirror. The image of the candle is located **A**. In front of the mirror, **B**. On the surface of the mirror, **C**. Behind the mirror, **D**. There is no image of the candle, **E**. Not enough information is given.

2. The height of the image of the candle is **A**. Larger than the candle, **B**. Smaller than the candle, **C**. The same size as the candle, **D.** There is no image of the candle, **E**. Not enough information is given.

3. In Figure 2, the candle is moved to the new location shown. The image of the candle as seen by the person is now **A**. To the left of where it was before, **B**. To the right of where it was before, **C**. In the same location as before, **D**. No image is seen by the person, **E**. Not enough information is given.

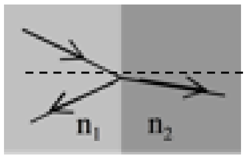
4. In Figure 3, the candle is moved back to its original location, and the person moves to the left to the new position shown. Compared to Figure 1, the location of the image of the candle is now **A**. To the left of where it was in Figure 1, **B**. To the right of where it was in Figure 1, **C**. In the same location as in Figure 1, **D**. There is no image of the candle, **E**. Not enough information is given.

5. The distance of the candle from the mirror is doubled. The height of the image of the candle is now **A**. Smaller than before, **B**. The same size as before, **C**. Larger than before, **D**. There is no image of the candle, **E**. Not enough information is given.

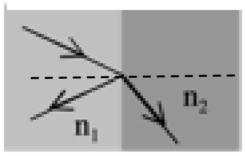
Questions 6-10 refer to a very narrow beam of light (for example, a laser beam) that can be represented by a single ray. The light is initially traveling from left to right in a transparent medium of index of refraction n_1, and incident on a second transparent medium of index of refraction n_2. The reflected and refracted rays are as shown in the diagrams below. (If either is missing, it means there is no reflected or no refracted ray.) Answer each of the questions below with one of the following choices, **A** through **F**.

A. Only if $n_2 > n_1$,
B. Only if $n_2 = n_1$,
C. Only if $n_2 < n_1$,
D. Can happen with **A** or **C**.
E. Never possible.
F. Always possible regardless of the relative sizes of the indexes of refraction.

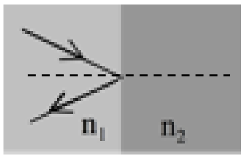
6. For which condition **A** through **F** could the rays be as shown in the figure?



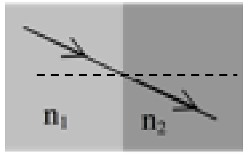
7. For which condition **A** through **F** could the rays be as shown in the figure?



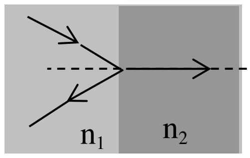
8. For which condition **A** through **F** could the rays be as shown in the figure?



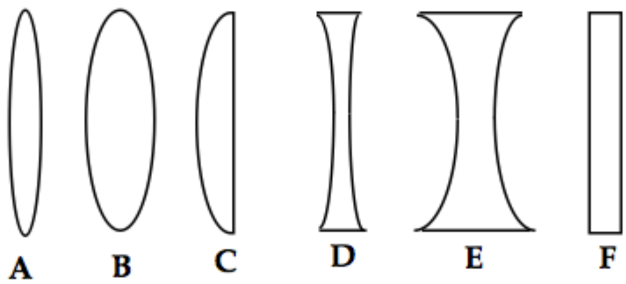
9. For which condition **A** through **F** could the rays be as shown in the figure?



10. For which condition **A** through **F** could the rays be as shown in the figure?



Questions 11-17 refer to the six lenses **A - F** shown on the right. All of the lenses are made of the same glass. Choose the lens that best answers each question below. There is only one correct answer for each question. If you think that none of the lenses is correct, choose answer **G**.



11. Which lens has the shortest positive focal length?
12. Light from the sun is focused by the lens to form a sharp spot on a piece of paper. Which lens must be held closest to the paper?
13. Which lens has the shortest negative focal length?
14. Which lens used as a magnifier would produce the largest magnification?

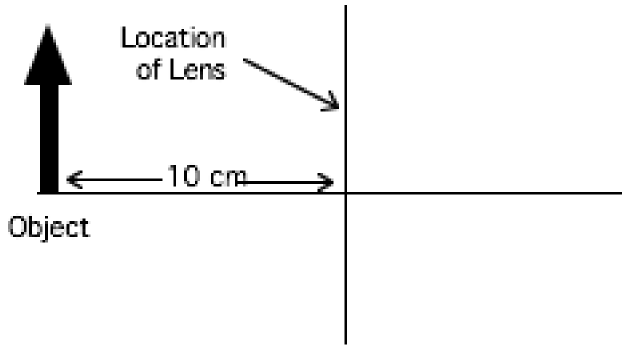
15. Which lens would give the largest correction to a person who is nearsighted? (Nearsighted people have distant objects focused in front of their retina. They can clearly see objects that are close to their eyes, but objects far away are blurred.)

16. Which lens has no focusing effect on light incident upon it?

17. Which lens would give the largest correction to a person who is farsighted? (Farsighted people have close objects focused behind their retina. They can clearly see objects that are far away from to their eyes, but objects that are close are blurred.)

Questions 18-22 refer to an object that is positioned 10 cm in front of a lens. The lens is either shaped like lens 1 or 2 shown below.

For each of the possible lenses in Questions 18-22, choose the one statement **A - D** that correctly describes the image formed by that lens. If none of the descriptions is correct, choose answer **E**.



A. The image is upright and larger than the object.
B. The image is upright and smaller than the object.
C. The image is inverted and larger than the object.
D. The image is inverted and smaller than the object.
E. None of the descriptions of the lens is correct.

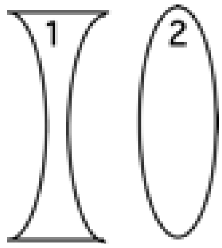
18. The lens looks like 1 with focal length 4 cm.

19. The lens looks like 2 with focal length 8 cm.

20. The lens looks like 2 with focal length 16 cm.

21. The lens looks like 2 with focal length 4 cm.

22. The lens looks like 1 with focal length 16 cm.

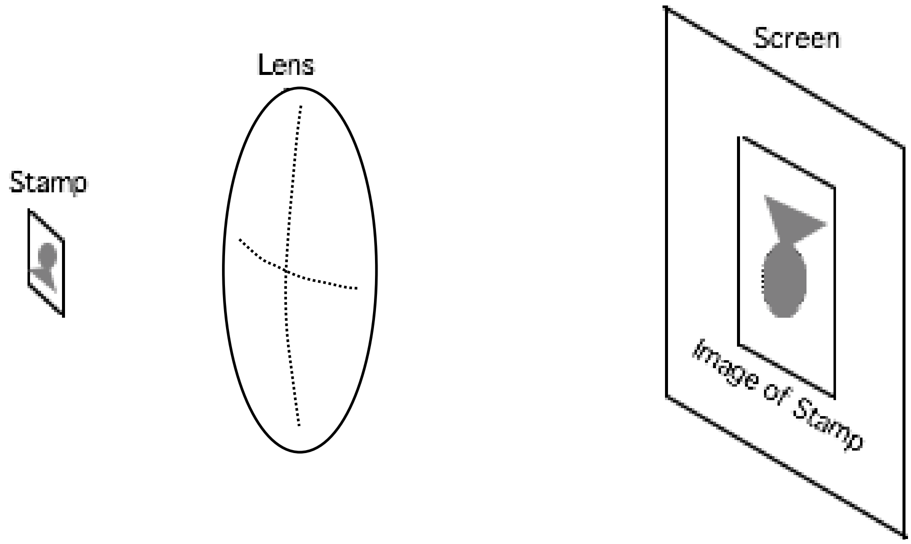


23. For a person with myopia (nearsightedness) the cornea and lens focus light from distant objects in front of the retina, causing blurred vision of distant objects. To correct myopia, the person should wear glasses (spectacles) with lenses that have which of the following prescriptions? **A.** A spherical lens with positive power, **B.** A spherical lens with negative power, **C.** A cylindrical lens with positive power, **D.** A cylindrical lens with negative power, **E.** A combination of spherical and cylindrical lenses, **F.** None of the above.

24. For a person with hyperopia (farsightedness) the cornea and lens focus light from near objects behind the retina, causing blurred vision of near objects. To correct hyperopia, the person should wear glasses (spectacles) with lenses that have which of the following prescriptions? **A.** A spherical lens with positive power, **B.** A spherical lens with negative power, **C.** A cylindrical lens with positive power, **D.** A cylindrical lens with negative power, **E.** A combination of spherical and cylindrical lenses, **F.** None of the above.

Questions 25-34 refer to the picture on the right. A stamp is placed to the left of the lens, and its image is formed on a screen to the right of the lens, as shown.

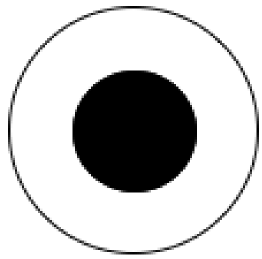
Choose the correct answer for each question.



25. Suppose the stamp is temporarily replaced (only for this question) with one twice as large. Which is true? **A.** The image will be whole but half as large, **B.** The image will disappear, **C.** The image will be dimmer, **D**. Only half of the image will be seen, **E**. The image will be twice as large, **F**. The image will be unchanged, **G**. None of these is correct.
26. Suppose the lens is temporarily replaced (only for this question) by a lens with half the diameter but with the same focal length. Which is true? **A.** Half of the image will disappear, **B.** The image will be whole but half as large, **C.** The image will disappear, **D.** The image will be dimmer, **E**. The image will be unchanged, **F**. None of these is correct.
27. Suppose that the screen is temporarily moved further away (only for this question) with the positions of the stamp and lens unchanged. Which is true? **A.** The image will be blurry, **B.** The image will be sharp but slightly larger, **C.** The image will be sharp but slightly smaller, **D**. The image will be unchanged, **E**. The image will disappear, **F**. None of these is correct.
28. Suppose the top half of the lens is temporarily covered by a piece of paper (only for this question) so that no light can pass through this portion. Which is true? **A.** Half of the image will disappear, **B.** The image will be whole but half as large, **C.** The image will disappear, **D.** The image will be dimmer, **E.** The image will appear on the paper, **F**. The image will be unchanged, **G**. None of these is correct.

Briefly explain your answer:

29. Suppose a circular piece of black tape temporarily covers the center of the lens (only for this question) as shown on the right. Which is true? **A**. The center of the image will disappear, **B**. The image will be whole but smaller, **C**. The image will disappear, **D**. The image will be dimmer, **E**. The image will appear on the tape, **F**. The image will be unchanged, **G**. None of these is correct.



30. Suppose half of the stamp is temporarily covered by a piece of paper (only for this question). What happens to the image of the stamp? **A.** Half of the image will disappear, **B.** The image will be whole but half as large, **C.** The image will disappear, **D.** The image will be dimmer, **E.** The image will appear on the paper, **F**. The image will be unchanged, **G**. None of these is correct.

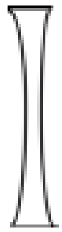
Briefly explain your answer:

31. Suppose that the stamp is temporarily moved slightly further away from the lens (only for this question). The screen is also moved to find the sharpest possible image. Which is true? **A.** The image is now larger than before, **B.** The image is now upright, **C.** The image is now the same size as before, **D.** The image is now smaller than before, **E.** None of these is correct.

Briefly explain your answer:

32. Suppose that the stamp is temporarily moved closer to the lens (only for this question). The screen is also moved to find the sharpest possible image. Which is true? **A.** The image is now smaller than before, **B.** The image is now the same size as before, **C.** If the object is moved close enough to the lens, it is possible that no sharp image will be found on the screen, **D.** The image on the screen will become upright, **E.** None of these is correct.

33. Suppose that the lens is temporarily replaced by one that looks like the one on the right (only for this question). The screen is moved to find the sharpest possible image. Which is true? **A.** The image will be larger, **B.** The image will be the same size, **C.** The image will be smaller, **D**. It will not be possible to find a sharp image on the screen, **E.** The image will be upright, **F.** None of these is correct.



34. Suppose the lens is removed. Which is true? **A.** The image will still be there but a little blurred, **B.** The image will be whole but smaller, **C.** The image will disappear, **D.** The image will be dimmer, **E**. The image will be unchanged, **F**. None of these is correct.

Briefly explain your answer:

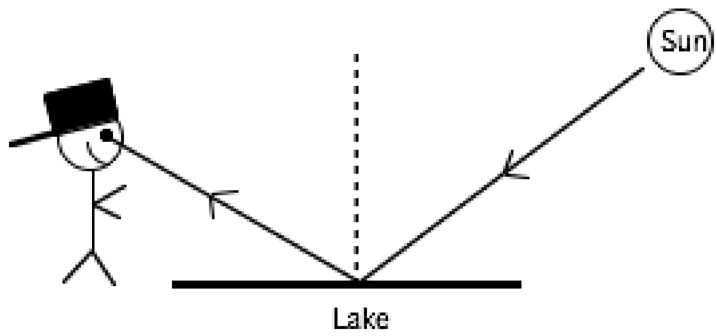
Questions 35-37 refer to a *perfect* polarizing filter that by definition passes 100% of light incident on it that is polarized along its axis, and 0% of light that is polarized perpendicular to its axis.

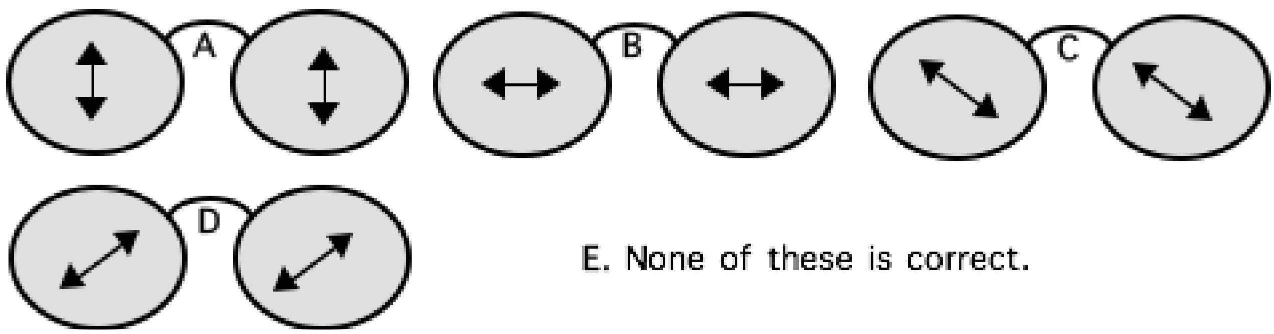
35. The light beam from a particular light source is un-polarized. The light is incident on the *perfect* polarizing filter with intensity 100. The transmitted intensity is **A**. 100, **B**. 75, **C**. 50, **D**. 25, **E**. 0, **F.** None of these is correct.

36. The light beam from a particular light source is linearly polarized with its axis of polarization *vertical*. The light is incident on the *perfect* polarizing filter with intensity 100. If the axis of the polarizing filter is vertical, the transmitted intensity is **A**. 100, **B**. 75, **C**. 50, **D**. 25, **E**. 0, **F.** None of these is correct.

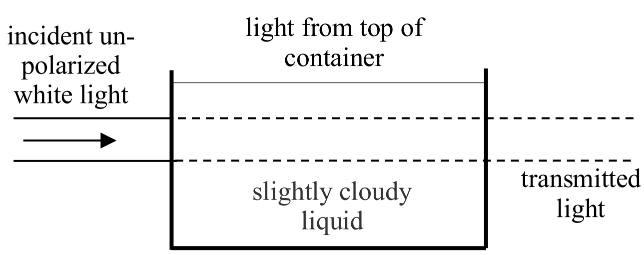
37. Now the *perfect* polarizing filter in question (36) is rotated so that its axis is *horizontal*. The transmitted intensity is now **A**. 100, **B**. 75, **C**. 50, **D**. 25, **E**. 0, **F.** None of these is correct.

38. Light from the sun can reflect into your eyes off the surface of a lake, as shown on the right. If you wear Polaroid sunglasses (made with polarizing filters), this reflection can be reduced. Which of the pictures below shows the correct direction of the axis of the polarizing filters in the sunglasses for the sunglasses to be most effective in blocking out the unwanted reflection from the lake?





Questions 39-42 refer to the experimental setup on the right. White, un-polarized light is incident from the left on a container filled with water made *slightly* cloudy by a small amount of dissolved milk. Observations are made on any light transmitted out through the other end of the container, and any light coming out from the top of the container.



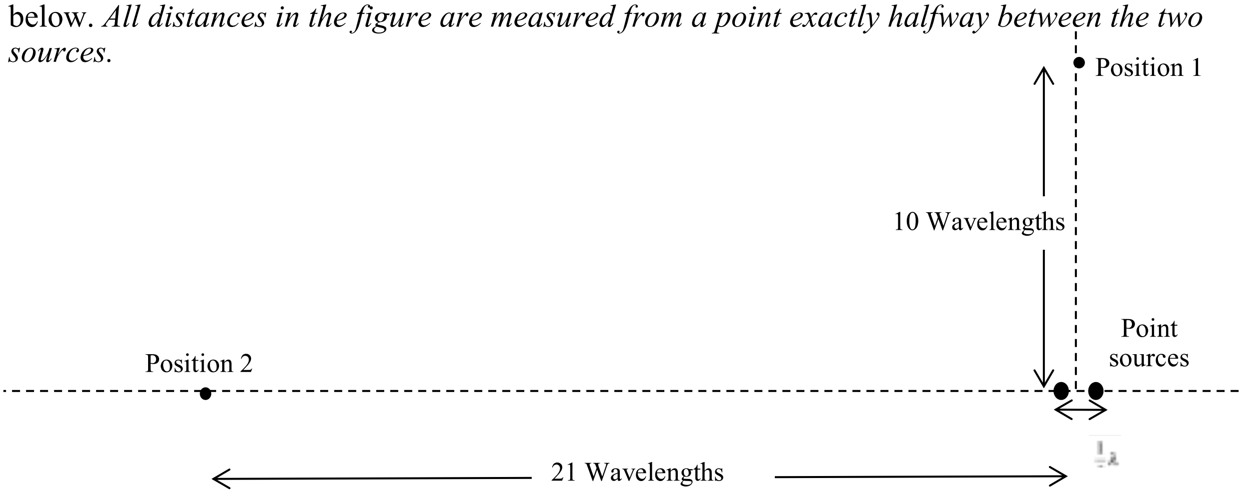
39. The transmitted light is **A.** White, **B.** Yellowish, **C.** Bluish, **D.** Greenish, **E.** There is no transmitted light, **F.** None of these is correct.

40. The light coming out from the top of the container is **A.** White, **B.** Yellowish, **C.** Bluish, **D.** Greenish, **E.** There is no light coming out from the top of the container, **F.** None of these is correct.

41. The transmitted light is **A.** Polarized with its axis vertical, **B.** Polarized with its axis horizontal, **C.** Polarized with its axis diagonal, **D.** Un-polarized, **E.** There is no transmitted light, **F.** None of these is correct.

42. The light coming out from the top of the container is **A.** Polarized with its axis vertical, **B.** Polarized with its axis horizontal, **C.** Polarized with its axis diagonal, **D.** Un-polarized, **E.** There is no light coming out from the top of the container, **F.** None of these is correct.

Questions 43-46 refer to two monochromatic point sources of light that are coherent with each other. They are separated by a distance equal to 1/2 wavelength, as shown in the figure below. *All distances in the figure are measured from a point exactly halfway between the two sources.*



43. When waves from the two point sources reach Position 1, which is directly above the halfway point between the two sources, they are **A**. Exactly in phase with each other, **B**. Exactly out of phase with each other, **C**. Neither in phase nor out of phase with each other, **D**. Not enough information is given.

44. Position 1 is a point of **A**. Completely constructive interference, **B**. Completely destructive interference, **C**. Neither constructive nor destructive interference, **D**. Not enough information is given.

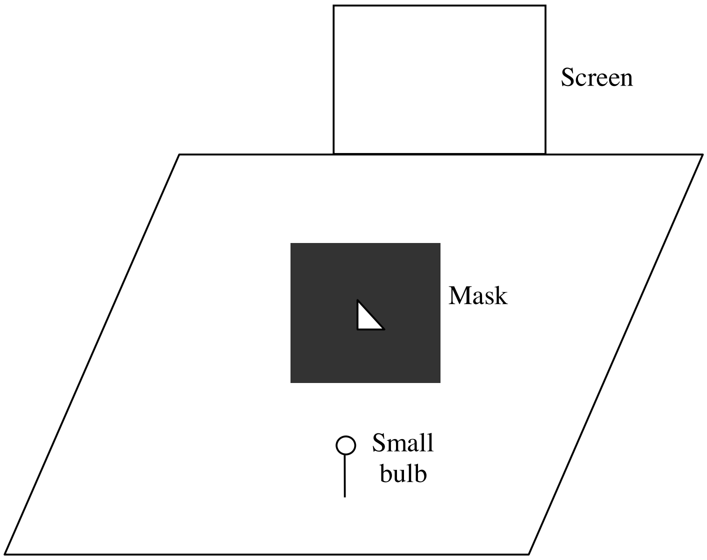
45. When waves from the two point sources reach Position 2, they are **A**. Exactly in phase with each other, **B**. Exactly out of phase with each other, **C**. Neither in phase nor out of phase with each other, **D**. Not enough information is given.

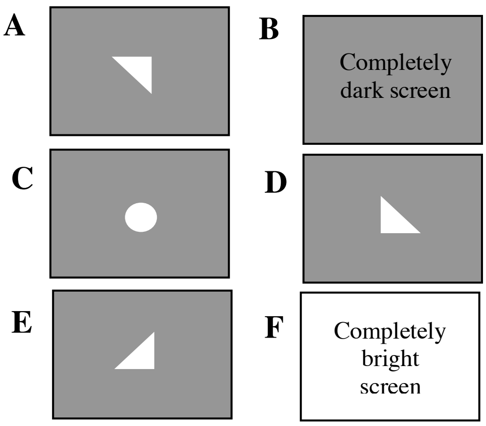
46. Position 2 is a point of **A**. Completely constructive interference, **B**. Completely destructive interference, **C**. Neither constructive nor destructive interference, **D**. Not enough information is given.

47. Laser light of wavelength 633 nm is directed on a narrow slit. A wide bright band of light and narrower bands on either side are seen on a screen a long distance away. Which of the following changes would result in a narrower bright central band on the screen? **A.** The slit is wider, **B.** The screen is further away, **C.** The slit is narrower, **D.** The wavelength is longer, **E.** The laser is closer to the slit, **F.** None of these will make the central band narrower, **G.** Not enough information is given.

48. Laser light of wavelength 633 nm is directed on two narrow parallel slits that have a very small separation. A series of bright and dark bands are seen on a screen a long distance away. Which of the following changes would result in a wider separation between two adjacent bands on the screen? **A.** The two slits are wider, **B.** The two slits are closer together, **C.** The two slits are narrower, **D.** The two slits are further apart, **E.** The screen is closer, **F.** The wavelength is shorter, **G.** The laser is further from the slits, **H.** None of these will make the separation wider, **J.** Not enough information is given.

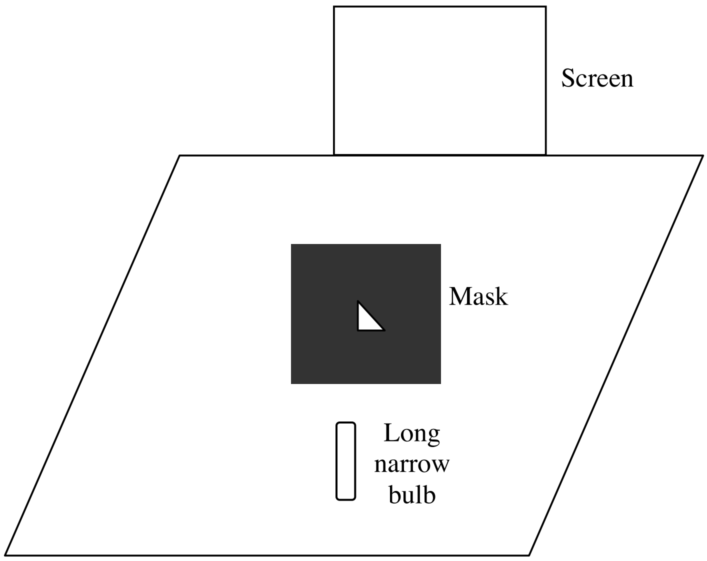
49. A very small light bulb is held in front of a screen. A mask with a triangular hole larger than the bulb is placed between the bulb and the screen as shown on the right. Which picture below correctly shows what will appear on the screen?

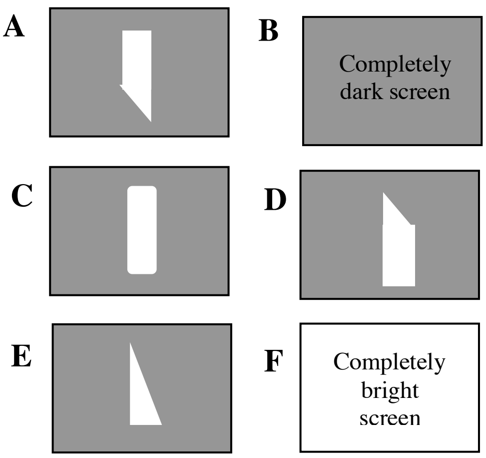




G. None of the above is correct.

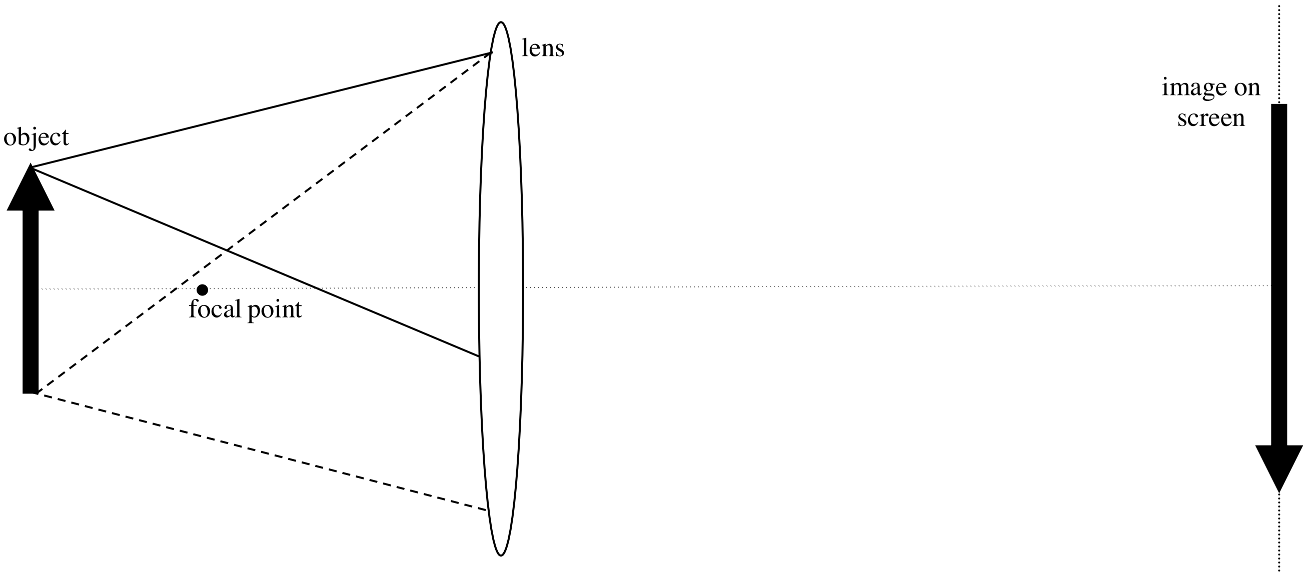
50. The bulb in (49) is replaced by a long, narrow bulb. Which picture below correctly shows what will appear on the screen?





G. None of the above is correct.

51. In the picture below, the object is to the left of the lens, at a distance from the lens that is larger than the focal length. The image is formed on a screen to the right of the lens as shown. Four rays of light are shown leaving points on the object. Continue those four rays through the lens to the screen.



Light and Optics Conceptual Evaluation Answer Sheet

Name____Class_________________________

_____1.	_____7.	____13.	____19.	____25.	____31.	____37.	____43.	____49.
_____2.	_____8.	____14.	____20.	____26.	____32.	____38.	____44.	____50.
_____3.	_____9.	____15.	____21.	____27.	____33.	____39.	____45.	
_____4.	____10.	____16.	____22.	____28.	____34.	____40.	____46.	
_____5.	____11.	____17.	____23.	____29.	____35.	____41.	____47.	
_____6.	____12.	____18.	____24.	____30.	____36.	____42.	____48.	

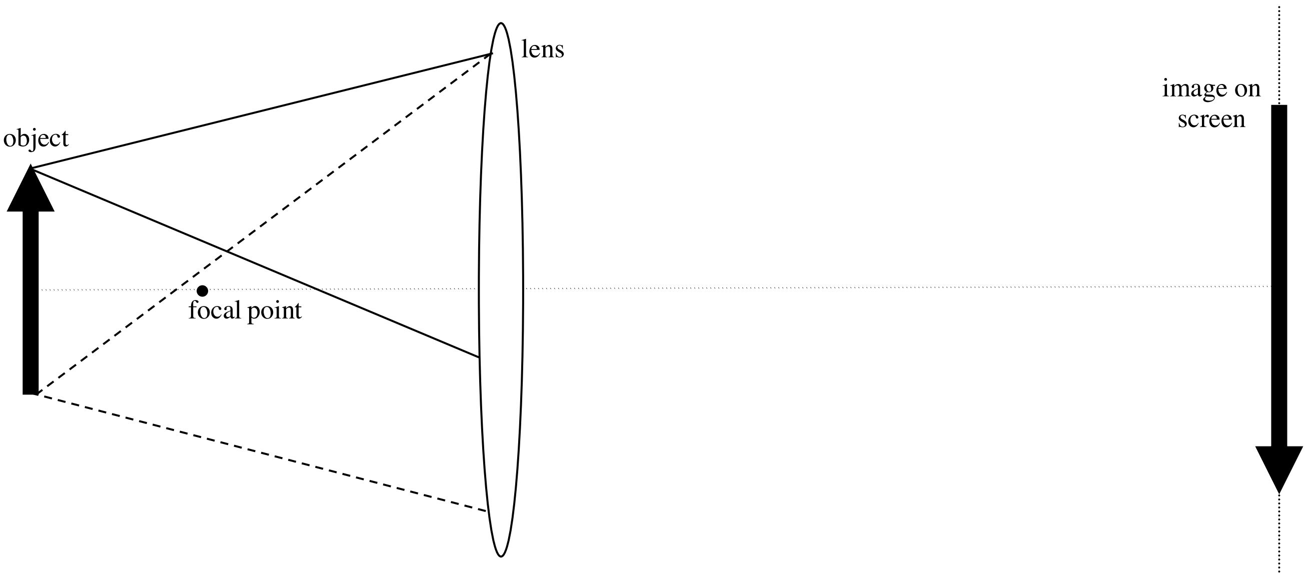
Briefly explain your answer to Question 28:

Briefly explain your answer to Question 30:

Briefly explain your answer to Question 31:

Briefly explain your answer to Question 34:

Question 51:



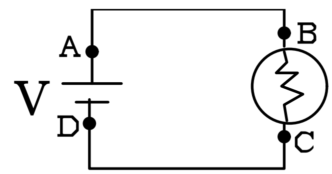
Name_____________________________ Lab Section: Day___________Time___________

DIRECTIONS: Use only a #2 or softer pencil on the scan sheet. Write your name above, and in the NAME space on the scan sheet (LAST NAME, *SPACE*, FIRST NAME and fill in the corresponding circles). No need to fill in your student number.

Answer questions 1-45 on the scan sheet by filling in the circle corresponding to the correct choice. Also include written answers for Questions 28, 30, 32 and 34 in the boxes below on these sheets.

On this test, all batteries are ideal (they have no internal resistance), and connecting wires have no resistance. Unlike most real bulbs, the resistances of the bulbs on this test do not change as the current through them changes.

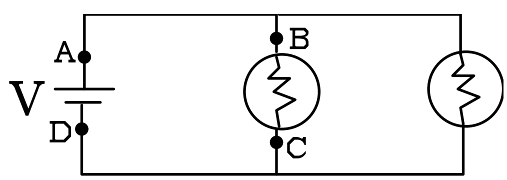
1. A bulb and a battery are connected as shown below.



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 everywhere.
- **F**. The current is the same between A and B and smaller than between C and D.
- **G**. The current is the same between A and B and larger than between C and D.
- **H**. The current is the same everywhere except in the bulb.
- **I**. The current is the same everywhere except in the battery.
- **J**. None of these is true.

For Questions 2-5, a second identical bulb is added to the circuit in Question 1, as shown below.



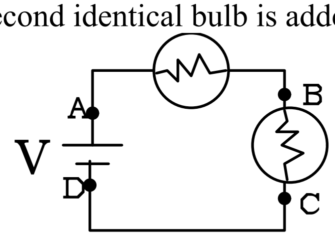
2. Compare the current at A now to the current at A before with only one bulb.
   - **A**. The current at A is now twice as large as before.
   - **B**. The current at A is now larger than before but not twice as large.
   - **C**. The current at A is the same as before.
   - **D**. The current at A is now half as large as before.
   - **E**. The current at A is now smaller than before but not half as large.
   - **J**. None of these is correct.

3. Compare the current through the bulb connected between B and C now to the current through it before when there was only one bulb.
   - **A**. The current is larger than it was before.
   - **B**. The current is the same as before.
   - **C**. The current is smaller than it was before.

4. Compare the brightness of the bulb connected between B and C now to its brightness before when there was only one bulb.
    A. The bulb is brighter than it was before.
    B. The bulb is just as bright as before.
    C. The bulb is dimmer than it was before.

5. Compare the potential difference across the bulb, V_{BC}, now to what it was before when there was only one bulb.
    A. The potential difference is now twice as large as before.
    B. The potential difference is now larger than before but not twice as large.
    C. The potential difference is the same as before.
    D. The potential difference is now half as large as before.
    E. The potential difference is now smaller than before but not half as large.
    J. None of these is correct.

For questions 6-8, a second identical bulb is added to the circuit in Question 1 as shown below.

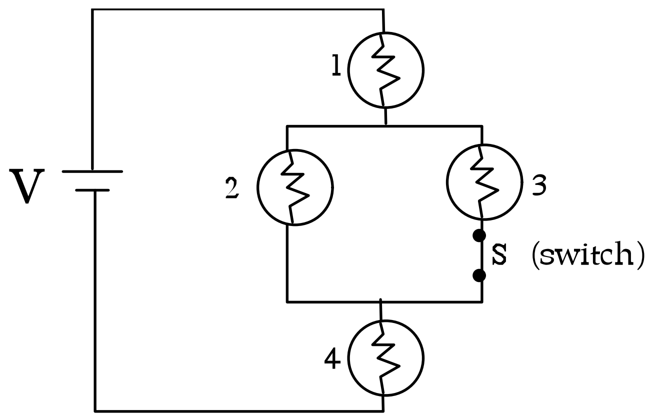


6. Compare the current at A now to the current at A with only one bulb.
    A. The current at A is now twice as large as before.
    B. The current at A is now larger than before but not twice as large.
    C. The current at A is the same as before.
    D. The current at A is now half as large as before.
    E. The current at A is now smaller than before but not half as large.
    J. None of these is correct.

7. Compare the potential difference across the bulb, V_{BC}, now to what it was before when there was only one bulb.
    A. The potential difference is now twice as large as before.
    B. The potential difference is now larger than before but not twice as large.
    C. The potential difference is the same as before.
    D. The potential difference is now half as large as before.
    E. The potential difference is now smaller than before but not half as large.
    J. None of these is correct.

8. Compare the brightness of the bulb connected between B and C to its brightness before when there was only one bulb.
    A. The bulb is brighter than it was before.
    B. The bulb is just as bright as before.
    C. The bulb is dimmer than it was before.

Questions 9-16 refer to the circuit below in which four identical bulbs are connected to a battery. (The switch, S, is initially closed as shown in the diagram.)



9.Which of the following correctly ranks the bulbs in brightness?

A. All bulbs are equally bright.
B. 1 is brightest, 2 next brightest, 3 next brightest and 4 dimmest
C. 1 is brightest. 2 and 3 are equally bright, and each is dimmer than 1. 4 is dimmest.
D. 1 and 4 are equally bright. 2 and 3 are equally bright, and each is dimmer than 1 or 4.
E. 2 and 3 are equally bright. 1 and 4 are equally bright, and each is dimmer than 2 or 3.
F. 1 is brightest, 4 is next brightest. 2 and 3 are equally bright, and each is dimmer than 4.
J. None of these is correct.

10. Which of the following correctly ranks the currents flowing through the bulbs?

A. All bulbs have the same current flowing through them.
B. The current through 1 is largest, 2 next largest, 3 next largest and 4 smallest.
C. The current through 1 is largest. 2 is the same as 3, and each is smaller than 1. 4 is smallest.
D. The current through 1 and 4 is the same. 2 is the same as 3, and each is smaller than 1 or 4.
E. The current through 2 and 3 is the same. 1 is the same as 4, and each is smaller than 2 or 3.
F. The current through 1 is largest, 4 is next largest. 2 is the same as 3, and each is smaller than 4.
J. None of these is correct.

11. Which of the following correctly ranks the potential differences across the bulbs?

A. All bulbs have the same potential difference across them.
B. The potential difference across 1 is largest, 2 next largest, 3 next largest and 4 smallest.
C. The potential difference across 1 is largest. 2 is the same as 3, and each is smaller than 1. 4 is smallest.
D. The potential difference across 1 is the same as 4. 2 is the same as 3, and each is smaller than 1 or 4.
E. The potential difference across 2 is the same as 3. 1 is the same as 4, and each is smaller than 2 or 3.
F. The potential difference across 1 is largest, 4 is next largest. 2 is the same as 3, and each is smaller than 4.
J. None of these is correct.

12. What happens to the current through bulb 1 if the switch, S, is opened?
    - **A**. It increases.
    - **B**. It remains the same.
    - **C**. It decreases.
    - **D.** Not enough information is given.

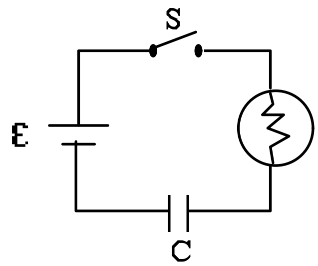
13. What happens to the current through bulb 2 if the switch, S, is opened?
    - **A**. It increases.
    - **B.** It remains the same.
    - **C.** It decreases.
    - **D.** Not enough information is given.

14. Based on your answer for items (12) and (13) compare the current through bulb 2 with the switch, S, opened to the current through bulb 1 before the switch was opened.
    - **A**. The current through bulb 2 now equals the current through bulb 1 before S was opened.
    - **B**. The current through bulb 2 now is more than half the current through bulb 1 before S was opened.
    - **C.** The current through bulb 2 now is half the current through bulb 1 before S was opened.
    - **D.** The current through bulb 2 now is less than half the current through bulb 1 before S was opened.
    - **E.** Not enough information is given.
    - **J.** None of these is correct.

15. Bulbs 2 and 3 are connected
    - **A.** In series.
    - **B.** In parallel.
    - **C.** In series and parallel.
    - **D.** Neither in series nor parallel.

16. Bulbs 1 and 3 are connected
    - **A.** In series.
    - **B.** In parallel.
    - **C.** In series and parallel.
    - **D.** Neither in series nor parallel.

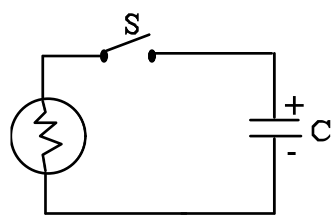
Questions 17-18 refer to the circuit below containing a battery, a capacitor, a bulb and a switch. The switch is initially open as shown in the diagram, and the capacitor is uncharged.



17. Which correctly describes what happens to the bulb when the switch is closed?
    - **A**. The bulb is dim and remains dim.
    - **B**. At first the bulb is dim and it gets brighter and brighter until its brightness levels off.
    - **C**. The bulb is bright and remains bright.
    - **D**. At first the bulb is bright and it gets dimmer and dimmer until it goes off.
    - **J**. None of these is correct.

18. Which correctly describes what happens after the switch has remained closed for a long time?
    - **A**. The bulb continues to shine brightly.
    - **B**. The bulb no longer shines.
    - **C**. The potential difference across the capacitor is steady and much smaller than ε.
    - **D**. The current in the circuit is steady and large.
    - **J**. None of these is correct.

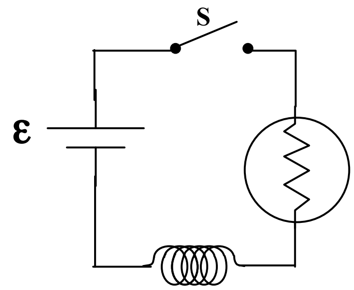
Questions 19-20 refer to the circuit below containing a capacitor, a bulb and a switch. The capacitor is initially charged, and the switch is initially open as shown in the diagram.



19. Which correctly describes what happens to the bulb when the switch is closed?
    - **A**. The bulb is dim and remains dim.
    - **B**. At first the bulb is dim and it gets brighter and brighter until its brightness levels off.
    - **C**. The bulb is bright and remains bright.
    - **D**. At first the bulb is bright and it gets dimmer and dimmer until it goes off.
    - **J**. None of these is correct.

20. Which correctly describes what happens after the switch has remained closed for a long time?
    - **A**. The bulb continues to shine brightly.
    - **B**. The bulb no longer shines.
    - **C**. The potential difference across the capacitor is steady.
    - **D**. The current in the circuit is steady and large.
    - **J**. None of these is correct.

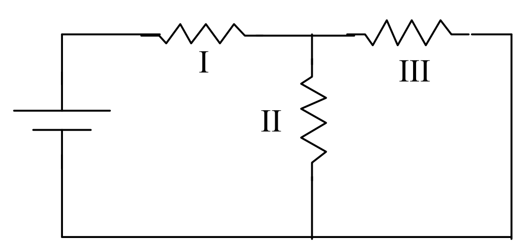
Questions 21-22 refer to the circuit below containing a battery, an inductor, a bulb and a switch. The switch is initially open as shown in the diagram.



21. Which correctly describes what happens to the bulb when the switch is closed?
    - **A**. The bulb is dim and remains dim.
    - **B**. At first the bulb is dim and it gets brighter and brighter until its brightness levels off.
    - **C**. The bulb is bright and remains bright.
    - **D**. At first the bulb is bright and it gets dimmer and dimmer until it goes off.
    - **J.** None of these is correct.

22. Which correctly describes what happens after the switch has remained closed for a long time?
    - **A**. The bulb continues to shine brightly.
    - **B**. The bulb no longer shines.
    - **C**. The potential difference across the inductor is steady and much smaller than **ε**.
    - **D.** The current in the circuit is zero.
    - **J.** None of these is correct.

Questions 23-24 refer to the diagram on the right of a circuit with three resistors.

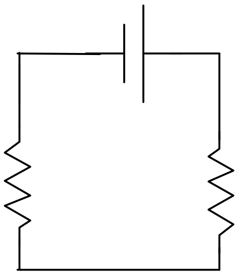


23. Which resistors in the diagram are in series?
    - **A.** I and II
    - **B.** I and III
    - **C.** II and III
    - **J.** None of these resistors are in series.

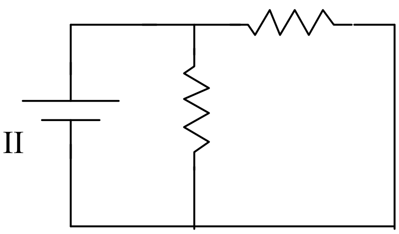
24. Which resistors in the diagram are in parallel?
    - **A.** I and II
    - **B.** I and III
    - **C.** II and III
    - **J.** None of these resistors are in parallel.

Questions 25-26 refer to the three circuit diagrams I, II and III on the right. All the resistors have different values.

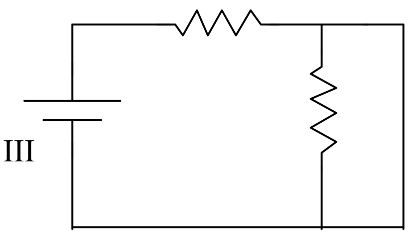
I



II



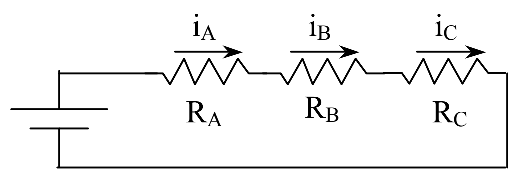
III



25. In which figure(s) are the two resistors in series?
    A. I
    B. II
    C. III
    D. I and II
    E. I and III
    F. II and III
    G. I, II, and III
    J. None of figures have resistors in series.

26. In which figure(s) are the resistors in parallel?
    A. I
    B. II
    C. III
    D. I and II
    E. I and III
    F. II and III
    G. I, II, and III
    J. None of figures have resistors in parallel.

Questions 27-28 refer to the figure on the right in which all three resistors are identical, $R_A = R_B = R_C$.

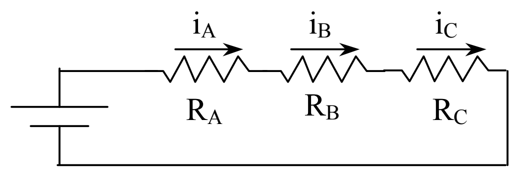


27. What can you say about the current i_A through R_A?
    A. $= i_B$, only
    B. $= i_C$, only
    C. $= i_B = i_C$
    D. $= i_B + i_C$
    E. $= i_B - i_C$
    J. None of these is correct.

28. What is the relationship between i_B and i_C?
    A. $i_B = 1/3\ i_C$
    B. $i_B = 1/2\ i_C$
    C. $i_B = i_C$
    D. $i_B = 2\ i_C$
    E. $i_B = 3\ i_C$
    J. None of there is correct.

Briefly explain in the space below how you arrived at your answer to Question 28.

Questions 29-30 refer to the figure on the right in which R_A is identical to R_B and their resistance is half of R_C, $R_A = R_B = 1/2\ R_C$.

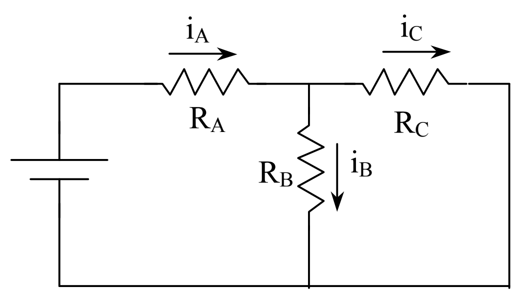


29. What can you say about the current i_A through R_A?
    - **A.** $= i_B$, only
    - **B.** $= i_C$, only
    - **C.** $= i_B = i_C$
    - **D.** $= i_B + i_C$
    - **E.** $= i_B - i_C$
    - **J.** None of these is correct.

30. What is the relationship between i_B and i_C?
    - **A.** $i_B = 1/3\ i_C$
    - **B.** $i_B = 1/2\ i_C$
    - **C.** $i_B = i_C$
    - **D.** $i_B = 2\ i_C$
    - **E.** $i_B = 3\ i_C$
    - **J.** None of these is correct.

Briefly explain in the space below how you arrived at your answer to Question 30.

Questions 31-32 refer to the figure on the right in which all three resistors are identical, $R_A = R_B = R_C$.

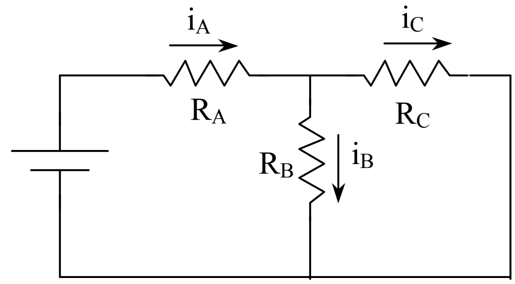


31. What can you say about the current i_A through R_A?
    - **A.** $= i_B$, only
    - **B.** $= i_C$, only
    - **C.** $= i_B = i_C$
    - **D.** $= i_B + i_C$
    - **E.** $= i_B - i_C$
    - **J.** None of these is correct.

32. What is the relationship between i_B and i_C?
    - **A.** $i_B = 1/3\ i_C$
    - **B.** $i_B = 1/2\ i_C$
    - **C.** $i_B = i_C$
    - **D.** $i_B = 2\ i_C$
    - **E.** $i_B = 3\ i_C$
    - **J.** None of these is correct.

Briefly explain in the space below how you arrived at your answer to Question 32.

Questions 33-34 refer to the figure on the right in which R_A is identical to R_B and their resistance is half of R_C, $R_A = R_B = 1/2\ R_C$

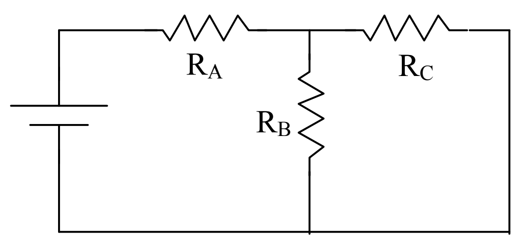


33. What can you say about the current i_A through R_A?
    - **A.** $= i_B$, only
    - **B.** $= i_C$, only
    - **C.** $= i_B = i_C$
    - **D.** $= i_B + i_C$
    - **E.** $= i_B - i_C$
    - **J.** None of these is correct.

34. What is the relationship between i_B and i_C?
    - **A.** $i_B = 1/3\ i_C$
    - **B.** $i_B = 1/2\ i_C$
    - **C.** $i_B = i_C$
    - **D.** $i_B = 2\ i_C$
    - **E.** $i_B = 3\ i_C$
    - **J.** None of these is correct.

Briefly explain in the space below how you arrived at your answer to Question 34.

Questions 35-36 refer to the circuit on the right in which R_A, R_B, and R_C all have different values.

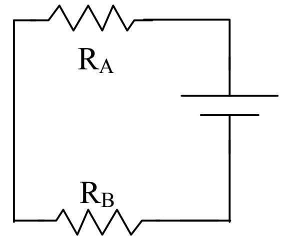


35. Which resistors in the diagram have the same magnitude of current running through them?
    - **A.** R_A and R_B
    - **B.** R_A and R_C
    - **C.** R_B and R_C
    - **D.** All of them.
    - **E.** There is not enough information.
    - **J.** None of them.

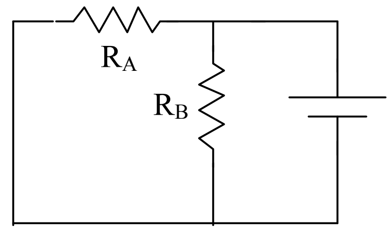
36. Which resistors in the diagram have the same potential difference across them?
    - **A.** R_A and R_B
    - **B.** R_A and R_C
    - **C.** R_B and R_C
    - **D.** All of them.
    - **E.** There is not enough information.
    - **J.** None of them.

Questions 37-38 refer to the circuits on the right in which R_A and R_B have different values.

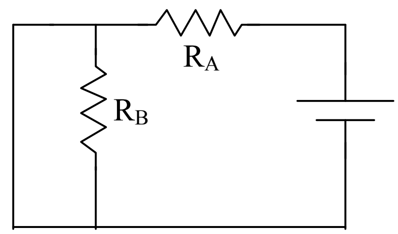
I



II



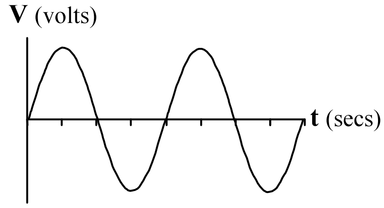
III



37. In which figure(s) do resistors R_A and R_B have the same current through them?
    - **A.** I
    - **B.** II
    - **C.** III
    - **D.** I and II
    - **E.** I and III
    - **F.** II and III
    - **G.** I, II, and III
    - **J.** None of figures have resistors that have the same current through them.

38. In which figure(s) do resistors R_A and R_B have the same potential difference across them?
    - **A.** I
    - **B.** II
    - **C.** III
    - **D.** I and II
    - **E.** I and III
    - **F.** II and III
    - **G.** I, II, and III
    - **J.** None of figures have resistors that have the same potential difference across them.

An AC signal generator, ~, produces a varying (sinusoidal) potential as a function of time indicated in the graph below.

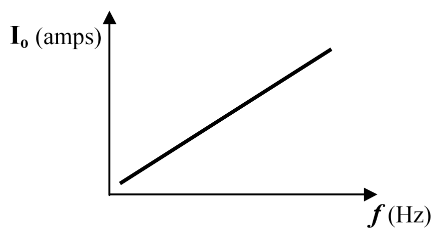


You connect this signal generator into four different circuits and record the maximum current measured by the ammeter, A, as you change the frequency of the signal. (The frequency is the time for one complete cycle.)You then plot maximum current as a function of frequency.

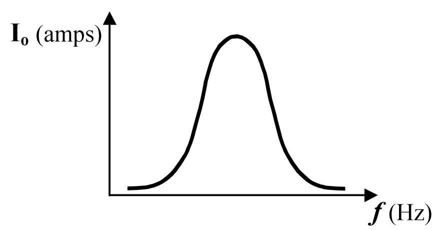
The other circuit elements are: a capacitor (**C**), ⊣⊢; an inductor (**L**), ; and a resistor (**R**), .

For each of the following four graphs choose a circuit, from the selection on the right, that has a current-frequency relationship characterized by that graph.

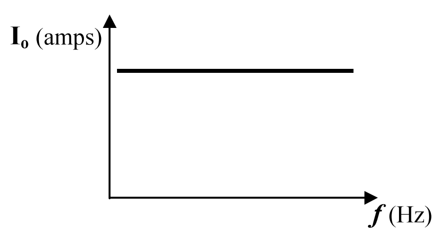
39)



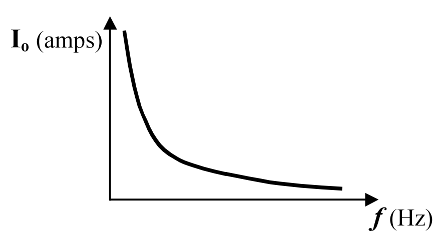
40)



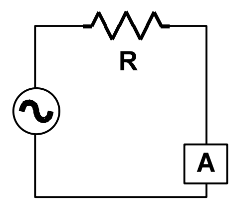
41)



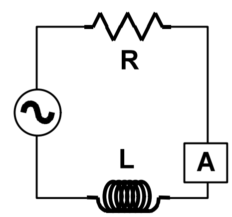
42)



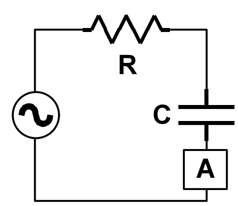
A



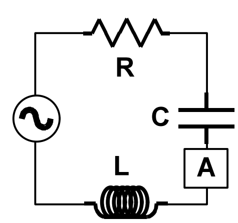
B



C

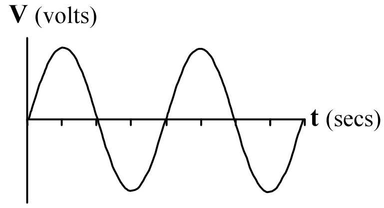


D



J None of these

An AC signal generator, ~, produces a varying (sinusoidal) potential as a function of time indicated in the graph below.

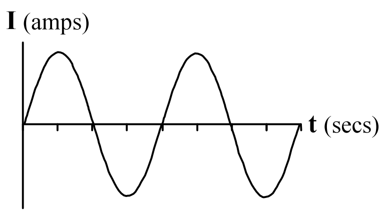


You connect this signal generator into three different circuits and plot the current measured by the ammeter, A, as a function of time.

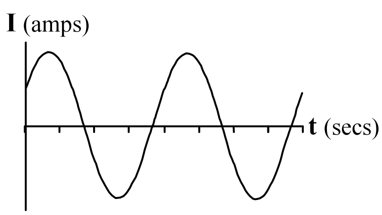
The other circuit elements are: a capacitor (**C**); an inductor (**L**); and a resistor (**R**).

For each of following three graphs choose a circuit, from the selection on the right, that has a current-time relationship characterized by that graph.

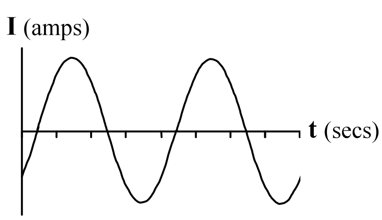
43)



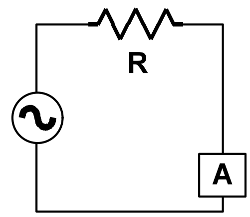
44)



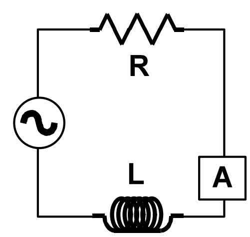
45)



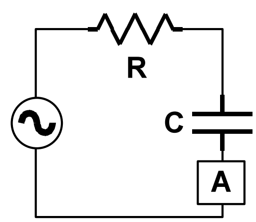
A



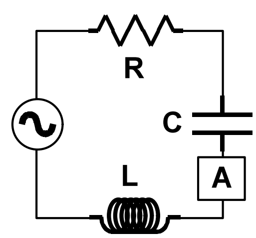
B



C



D



J None of these

Name: **Class:** **Date:**

ELECTRIC CIRCUIT CONCEPTUAL EVALUATION
ANSWER SHEET

1.	A	B	C	D	E	F	G	H	I	J
2.	A	B	C	D	E	F	G	H	I	J
3.	A	B	C	D	E	F	G	H	I	J
4.	A	B	C	D	E	F	G	H	I	J
5.	A	B	C	D	E	F	G	H	I	J
6.	A	B	C	D	E	F	G	H	I	J
7.	A	B	C	D	E	F	G	H	I	J
8.	A	B	C	D	E	F	G	H	I	J
9.	A	B	C	D	E	F	G	H	I	J
10.	A	B	C	D	E	F	G	H	I	J
11.	A	B	C	D	E	F	G	H	I	J
12.	A	B	C	D	E	F	G	H	I	J
13.	A	B	C	D	E	F	G	H	I	J
14.	A	B	C	D	E	F	G	H	I	J
15.	A	B	C	D	E	F	G	H	I	J
16.	A	B	C	D	E	F	G	H	I	J
17.	A	B	C	D	E	F	G	H	I	J
18.	A	B	C	D	E	F	G	H	I	J
19.	A	B	C	D	E	F	G	H	I	J
20.	A	B	C	D	E	F	G	H	I	J
21.	A	B	C	D	E	F	G	H	I	J
22.	A	B	C	D	E	F	G	H	I	J
23.	A	B	C	D	E	F	G	H	I	J
24.	A	B	C	D	E	F	G	H	I	J
25.	A	B	C	D	E	F	G	H	I	J
26.	A	B	C	D	E	F	G	H	I	J
27.	A	B	C	D	E	F	G	H	I	J
28.	A	B	C	D	E	F	G	H	I	J
29.	A	B	C	D	E	F	G	H	I	J
30.	A	B	C	D	E	F	G	H	I	J
31.	A	B	C	D	E	F	G	H	I	J
32.	A	B	C	D	E	F	G	H	I	J
33.	A	B	C	D	E	F	G	H	I	J
34.	A	B	C	D	E	F	G	H	I	J
35.	A	B	C	D	E	F	G	H	I	J
36.	A	B	C	D	E	F	G	H	I	J
37.	A	B	C	D	E	F	G	H	I	J
38.	A	B	C	D	E	F	G	H	I	J
39.	A	B	C	D	E	F	G	H	I	J
40.	A	B	C	D	E	F	G	H	I	J
41.	A	B	C	D	E	F	G	H	I	J
42.	A	B	C	D	E	F	G	H	I	J
43.	A	B	C	D	E	F	G	H	I	J
44.	A	B	C	D	E	F	G	H	I	J
45.	A	B	C	D	E	F	G	H	I	J