Assessing student learning of Newton's laws: The Force and Motion Conceptual Evaluation and the Evaluation of Active Learning Laboratory and Lecture Curricula

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In this paper, we describe the Force and Motion Conceptual Evaluation, a research-based, multiple-choice assessment of student conceptual understanding of Newton's Laws of Motion. We discuss a subset of the questions in detail, and give evidence for their validity. As examples of the application of this test, we first present data which examine student learning of dynamics concepts in traditional introductory physics courses. Then we present results in courses where research-based active learning strategies are supported by the use of microcomputer-based (MBL) tools. These include (1) *Tools for Scientific Thinking Motion and Force* and *RealTime Physics Mechanics* laboratory curricula, and (2) microcomputer-based *Interactive Lecture Demonstrations*. In both cases, there is strong evidence, based on the test, of significantly improved conceptual learning.

I. INTRODUCTION

In this paper, we discuss the Force and Motion Conceptual Evaluation[1] (FMCE), and its use to evaluate student learning in introductory physics courses. This research-based, multiple-choice assessment instrument was designed to probe conceptual understanding of Newtonian mechanics. Results obtained on a subset of questions that were asked before and after instruction demonstrate that students are little affected by the traditional approach. In an effort to address this problem, we have developed two active learning, microcomputer-based laboratory (MBL) curricula, *Tools for Scientific Thinking Motion and Force* and *RealTime Physics Mechanics*. We have also developed *Tools for Scientific Thinking Interactive Lecture Demonstrations*, a general strategy to encourage active learning in large lecture classes, or in any situation in which only one computer is available. After describing the test and giving arguments for its validity, we describe its application in the assessment of the effectiveness of these three curricula in helping students develop a functional understanding of the first and second laws.[2]

II. CONTEXT FOR THE INVESTIGATION

While we and others have evaluated large numbers of students at many colleges, universities, and high schools with the FMCE, we have had the opportunity to do our most extensive controlled testing at the University of Oregon, in the noncalculus (algebra-based) and calculus-based general physics lecture courses and in the introductory physics laboratory, and at Tufts University in both the noncalculus and calculus-based courses with laboratories.

At Oregon, the noncalculus lecture course generally enrolls between 400 and 500 students divided among either two or three lecture sections. The calculus-based course enrolls 60–90 students in one lecture section. The laboratory is a separate course, with weekly experiments, enrolling about 250 students from both of these lecture courses. The fact that as many as half of the students in these courses are not enrolled in the laboratory has allowed us to divide the students in each course into two research study groups. One group consists of students who are only enrolled in lecture, and will be referred to below as the NOLAB group. The other group is enrolled in both lecture and laboratory and will be referred to as the LAB group.

At Tufts, the noncalculus physics course enrolls 160 to 200 students in a single lecture section. As part of this course, almost all of these students take the laboratory, in which they do a new lab every two weeks. (Enrollment in the lab sections is a mix of students from both the noncalculus and calculus-based courses.) In addition to a large calculus-based course in the Fall, Tufts offers an off-semester section in the Spring. Almost all of the 50–70 students in this section also are enrolled in a laboratory which meets every week. These students are statistically more likely to have trouble with physics than those in the Fall course, and many have postponed taking physics to increase their chances of success.

III. DESCRIPTION OF THE FMCE

In previous studies, we have reported on the evaluation of student understanding of *kinematics* concepts using a series of multiple-choice questions.[3] Some of these questions are included in the FMCE.[4] In this paper, we will focus on four sets of questions from the FMCE that probe students' views of force and motion (dynamics) concepts, the ''Force Sled'' questions (questions 1–7), the ''Cart on Ramp'' questions (questions 8–10), the ''Coin Toss'' questions (questions 11–13), and the ''Force Graph'' questions (questions 14–21). Appendix A contains the complete FMCE.[1] Most physics professors thought initially that these questions were much too simple for their students and expected that most would answer in a Newtonian way after traditional physics instruction at a selective university. After seeing typical responses to these questions in which fewer than 10% of the students

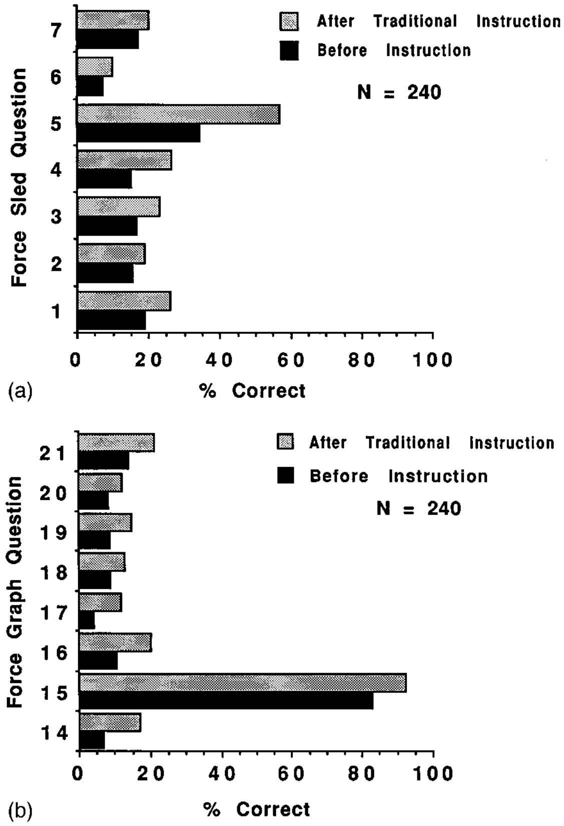

Fig. 1. Effect of traditional instruction on students' answers to the Force Sled (Natural Language) and Force Graph (Graphical) questions from the FMCE. Percent of a matched group of 240 University of Oregon noncalculus general physics students who answered (a) each Force Sled question and (b) each Force Graph question in a Newtonian manner before and after traditional instruction in 1989–1990.

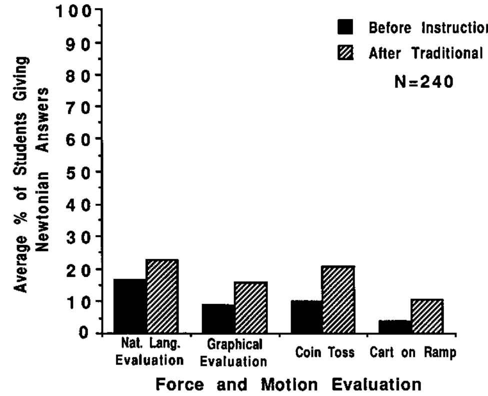

Fig. 2. Student understanding of dynamics before and after traditional instruction. Percent of a matched group of 240 University of Oregon noncalculus general physics students who answered groups of dynamics questions in a Newtonian manner before and after traditional instruction in 1989–1990. The Natural Language Evaluation is a composite of the Force Sled questions, and the Graphical Evaluation is a composite of the Force Graph questions. All three Coin Toss and Cart on Ramp questions had to be answered correctly for the answers to be considered Newtonian.

seem to change their views of dynamics after traditional instruction, some professors suggested that perhaps the questions are not significant (or valid and reliable) measures of students' knowledge. Our research does not support this point of view, and we will discuss evidence for the validity of the questions after looking at some actual research results.

Figure 1(a) and (b) shows the percentage of 240 noncalculus NOLAB students at Oregon during 1989 and 1990 who answered the Force Sled questions and Force Graph questions in a Newtonian way. The questions were administered both before and after traditional instruction on dynamics, which included standard lectures, homework problems, quizzes, and exams. These results show that less than 20% of the students answered dynamics questions in ways that are consistent with a Newtonian view of the world either before or after traditional instruction. (See the discussion of Force Graph question 15 in Sec. IV, below.) These results are typical and not unique to Oregon. Identical questions were asked before and after instruction. The pre-test was not returned nor discussed with the students. It is clear that asking the same questions twice could not have had a large instructional effect, since the total change before and after traditional instruction averaged about 7%. The results from this pre-test (and those that follow) show that very few students entering a university general physics course, including those who have previously studied physics, understand dynamics from a Newtonian point of view. Unhappily, the post-test results show that only a small percentage of students adopt a Newtonian framework, even after well executed traditional instruction. These observations are consistent with other research into student understanding of dynamics.[4–15]

The results of the Cart on Ramp and the Coin Toss, which are shown in Fig. 2 for this same group of students, indicate that very few students answer these questions as a physicist would. We consider that these questions have been answered from a Newtonian point of view *only* when the choices *on all three questions* indicate a constant force downward for the Coin Toss and downward along the ramp for the Cart on Ramp. (Essentially all student models result in the Newtonian answer for the question in each set referring to downward motion.)

These questions have been asked of thousands of students. The fact that traditional instruction has little effect on students' beliefs about force and motion, as shown by the results in Figs. 1 and 2, is confirmed by considerable additional research.

IV. DISCUSSION OF THE DYNAMICS QUESTIONS ON THE FMCE

The FMCE is most useful when correlations among student answers on different questions are examined. In this paper, however, we are concerned primarily with the percentage of students answering questions in a Newtonian way in order to evaluate traditional instruction and our active learning curricula.

It will be useful to look more closely at the questions in order to determine their ability to probe students' ideas. Note that although both the Force Sled and the Force Graph questions explore the relationship between force and motion by asking about similar motions, the two sets of questions are very different in a number of ways. The Force Sled questions make no reference to graphs and no overt reference to a coordinate system. They use ''natural'' language as much as possible, and they explicitly describe the force acting on the moving object. On the other hand, the Force Graph questions use a graphical representation, make explicit references to coordinate systems, and do not explicitly describe the force that is acting. It is easier to ask more complex questions using the more precise graphical representation. In spite of these differences in the two types of questions, students' responses are very similar where there is an exact analog between the Force Sled and Force Graph questions. In the few cases where students do very much better answering the Force Graph questions than the Force Sled questions, it is possible that their English language skills are weak.

Some questions serve specific purposes. Force Sled question 5 is intended to identify statistically students who are just beginning to consider Newton's First Law as a description of the world. It is very similar to question 2 but is designed to elicit the Newtonian answer of zero net force for motion at constant velocity. Students who are beginning to accept a Newtonian view statistically choose ''no applied force needed'' for this question, even while answering Force Sled question 2 (and Force Graph question 14) by choosing a constant force in the direction of motion. Students who are far from consistently adopting a Newtonian view, still answer Force Sled question 5 by picking a nonzero applied force. Thus question 5 helps identify students who are beginning to have doubts about their previous views but are not entirely convinced. It is not a good indicator of firm Newtonian thinking. Note that many more students answered this question in a Newtonian way both before and after traditional instruction than other similar questions.

Force Sled question 6 was originally intended to probe directly whether students believed that the net force is in the direction of the acceleration, but further research showed that many students who believed this still chose the ''wrong'' answer. (Note that the answer is directly contained in the question.) When asked to reconsider their answer, these students would change it to B, the Newtonian answer. Up to 40% of physics faculty also choose an answer other than B (almost always F). After discussion, they agree the answer should be B, but see no way to make the question clearer. This result indicates that a ''wrong'' answer to question 6 does not necessarily indicate non-Newtonian reasoning. Since some people very consistently answer all other questions from a Newtonian viewpoint while still missing question 6, we must interpret the results cautiously. Such results confirm the value of asking a variety of questions of diverse audiences to probe understanding of particular concepts.

The combination of Force Sled questions 1–4 and 7, on the other hand, indicate reliably (in a statistical sense) the prevalence of non-Newtonian and Newtonian student views. We will use a composite average of the results on these five questions in the comparisons that follow and label this average as the ''natural language evaluation.'' Figure 2 shows this average for the data already presented in Fig. 1(a) before and after traditional instruction.

Some questions are asked to make sure that students can read English, can understand the format, and/or can interpret graphs. Question 15 in the Force Graph sequence, which asks for the force on an object which is at rest, is the only single question in which the most common student view and Newtonian view are the same. Consequently, it is answered the same way by a physicist and by 85% to 95% of students even before instruction. If a large percentage of students answer this question incorrectly (common for middle school students), it is likely that many of these students are unable to read graphs.

Force Graph question 20 is, statistically, one of the last questions in this set answered correctly, even by students who answer the other questions in a Newtonian way. We will

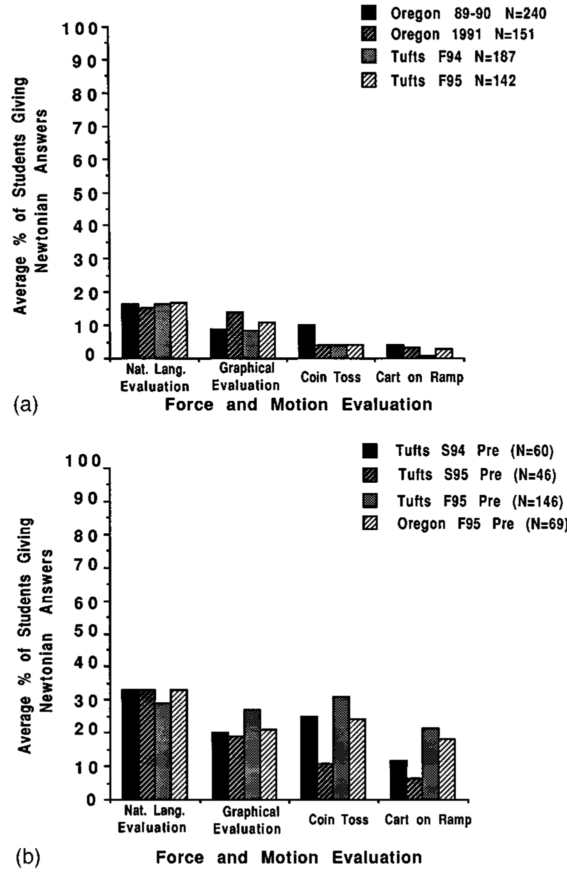

Fig. 3. Comparison of understanding of dynamics before instruction in (a) noncalculus and (b) calculus-based introductory physics courses at Oregon and Tufts.

use a composite average of the seven questions, 14 and 16 through 21, to make comparisons and label them the ''graphical evaluation.'' Figure 2 shows this average for the data already presented in Fig. 1(b) before and after traditional instruction. (It is not possible to compare directly student ability to answer natural language or graphical questions in terms of the averages we have just defined, since the Force Sled and Force Graph questions included in the averages are not direct analogs.)

We have tracked conceptual understanding of Newton's First and Second Laws of incoming students at Oregon and Tufts over a number of years and find very stable results. Some results for students entering noncalculus physics courses are shown in Fig. 3(a). Results for calculus-based introductory courses are shown in Fig. 3(b). Notice that the variations between courses or institutions are generally *larger* than the small changes which result from traditional instruction (shown in Figs. 1 and 2).

V. CONCEPTUAL UNDERSTANDING OF DYNAMICS BEFORE AND AFTER ACTIVE LEARNING LABORATORIES

The Tools for Scientific Thinking (TST) Motion and Force[16] and *RealTime Physics (RTP) Mechanics*[17] MBL laboratory curricula, developed for the introductory laboratory at universities, colleges, and high schools, are designed to allow students to take an active role in their learning and encourage them to construct physical knowledge for them-

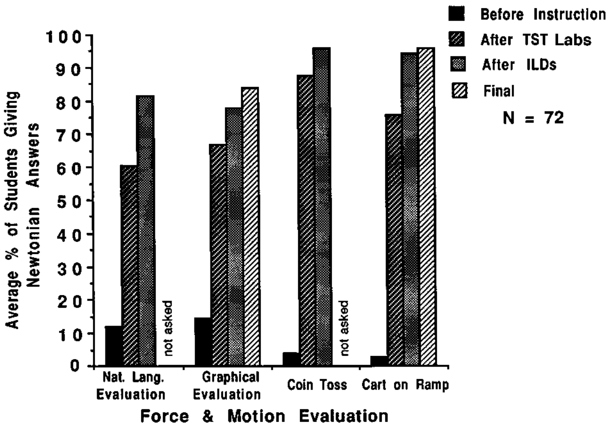

Fig. 4. Effect of *TST Motion and Force* labs and *Interactive Lecture Demonstrations* on understanding of dynamics in 1991 Oregon noncalculus general physics.

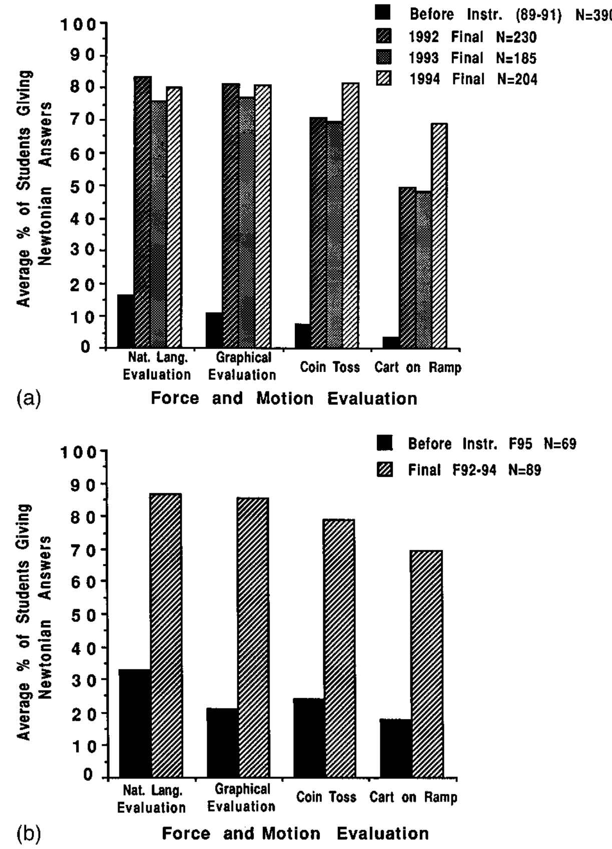

Fig. 5. Effect of *RTP Mechanics* labs on understanding of dynamics in 1992–1994 Oregon (a) noncalculus and (b) calculus-based general physics.

selves from actual observations. These curricula have been described in more detail elsewhere.[4,7,18] They make substantial use of the results of physics education research.[4–15] Both were designed to introduce active learning into the laboratory portion of a traditionally structured introductory course. Both use the MBL force probe and motion detector to measure and display the force applied to an object and its motion (position, velocity, and/or acceleration) simultaneously in real time.[19] They use a guided discovery approach and are intended for student groups of two to four. They support the peer learning that is possible when data are immediately presented in an understandable form. They engage students through a learning cycle which includes predictions, observations, and comparisons. In addition, they pay attention to student alternative understandings that have been documented in the research literature.

The *TST Motion and Force* curriculum, released in 1992, was designed to help improve conceptual understanding in mechanics by substituting a small number of active learning laboratories for traditional ones. The *RTP Mechanics* curriculum, released in 1994, has the more ambitious goal of completely replacing the entire introductory laboratory with a sequenced, coherent set of active learning laboratories. The origins of *RTP Mechanics* lie in *TST Motion and Force* and *Workshop Physics*.[20]

How well do students understand dynamics concepts after completing the *TST* and *RTP* active learning laboratories? During 1989–1991, the LAB students in the Oregon noncalculus general physics course completed all of the *TST Motion and Force* labs. In 1991, they were evaluated with the FMCE a number of times during the term, largely to measure the effectiveness of *Interactive Lecture Demonstrations*. (See Sec. VI.) However, we were also able to evaluate the LAB group's conceptual understanding after they had completed the *TST Motion and Force* labs. As can be seen in Fig. 3(a), the pre-test results for the group of students in 1991 are very similar to results in other years. The same questions (with the order rearranged) were asked of the LAB group after the students completed the two *TST* kinematics and two *TST* dynamics laboratories, about five weeks after the pre-test. During this period, the students also experienced about one lecture of special kinematics *Interactive Lecture Demonstrations*.

The first two bars of Fig. 4 show the results for the same group of 72 LAB students before instruction and then after lectures and laboratories. As can be seen, there are very significant improvements even though the post-test was given immediately after the last laboratory, before the students had much time to assimilate their knowledge of these concepts. (As shown in the last two bars of Fig. 4, more than 90% of these LAB students were answering most questions in a Newtonian manner by the end of the course. This additional improvement was achieved through dynamics *Interactive Lecture Demonstrations*, as described in Sec. VI.)

From 1992 to 1994, students in the Oregon introductory laboratory completed the *RTP Mechanics* laboratories. Because research, as shown in Fig. 3(a), shows that the pre-test results vary little from year to year, no pre-test was given during these years, but the FMCE was part of the laboratory final examination. In Fig. 5(a), the final results for the LAB group from the noncalculus general physics course in each year, 1992 through 1994, are compared to the average pre-test results for 1989–91. These results should also be compared to the 7% gain achieved by traditional instruction on these questions, shown in Fig. 2. (The additional improvement in the Coin Toss and Cart on Ramp questions in 1994 is attributable to a curricular change in *RTP Mechanics*, which placed more emphasis on motion caused by the gravitational force.)

A much smaller LAB group of students in the calculus-based general physics course at Oregon in 1992–94 also completed the *RTP Mechanics* laboratories and the lab final. These results are shown in Fig. 5(b). While no pre-test was given to these classes, the 1995 pre-test results for the same

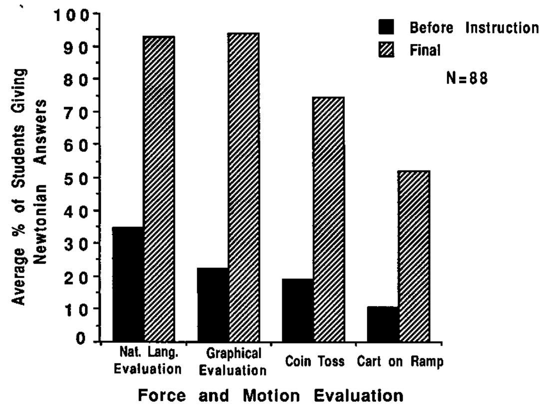

Fig. 6. Effect of *RTP Mechanics* labs on understanding of dynamics in Spring, 1994–1995 Tufts calculus-based introductory physics.

course are included for comparison. This seems reasonable, since the pre-test data for calculus-based courses shown in Fig. 3(b) are all very consistent with one another.

The students in the Spring (off-semester) introductory calculus-based course at Tufts also did the *RTP Mechanics* laboratories during the Springs of 1994 and 1995. The results on the FMCE for a combined group of 88 students from both years is shown in Fig. 6 before all instruction and on the final examination.

Figure 7 compares results on the FMCE after traditional instruction in introductory noncalculus physics courses and after experiencing the *RTP Mechanics* labs in noncalculus and calculus-based courses. The significant improvement in conceptual understanding as a result of the labs is very similar in calculus and noncalculus courses and similar for students at Oregon and at Tufts.

VI. CONCEPTUAL UNDERSTANDING OF DYNAMICS BEFORE AND AFTER INTERACTIVE LECTURE DEMONSTRATIONS

Despite considerable evidence that traditional approaches are ineffective in teaching physics concepts,[3–15] most physics students in this country continue to be taught in lectures, often in large lectures with more than 100 students. Also,

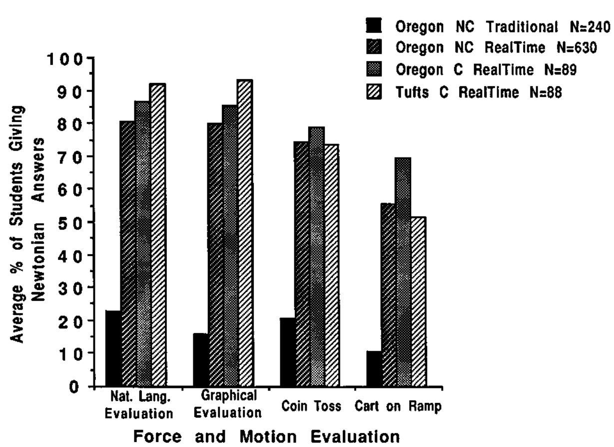

Fig. 7. Understanding of dynamics in noncalculus (NC) and calculus-based (C) courses at Oregon and Tufts which included *RTP Mechanics* labs compared to that with traditional instruction.

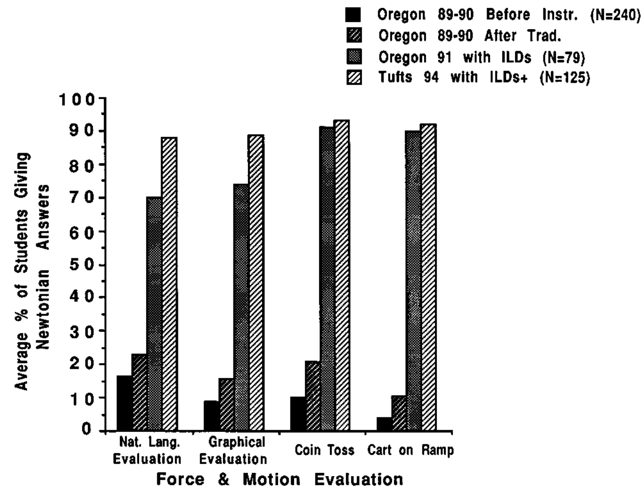

Fig. 8. Understanding of dynamics in non-calculus courses at Oregon and Tufts with *ILD*-enhanced instruction compared to that with traditional instruction.

many high school and college physics programs are unable to support hands-on laboratory work for large numbers of students because they have only a few computers.

After several years of research, we formalized in 1991 a procedure for the *Tools for Scientific Thinking Interactive Lecture Demonstrations* (*ILDs*), which engages students in the learning process and, therefore, converts the usually passive lecture environment to a more active one. The procedure involves students recording individual predictions of the outcomes of simple experiments on a Prediction Sheet (which is collected), discussing their predictions with neighbors and then comparing their predictions to the actual results displayed for the class with MBL tools. We have published four sequences of mechanics *ILDs* to enhance the learning of kinematics and dynamics, including Newton's Three Laws. More details on the procedure and design, as well as descriptions of these four *ILD* sequences, will be found elsewhere.[4–7,21,22]

Here we report on assessments of conceptual learning gains using the FMCE for introductory physics students who experienced series of *ILDs* on kinematics and Newton's First and Second Laws. In the Fall of 1991, as a substitute for traditional instruction, students in the noncalculus general physics class at Oregon experienced *about two full lectures of ILDs* on kinematics and dynamics. A similar set of *ILDs* was carried out in the noncalculus introductory physics class at Tufts, during Fall, 1994. At Tufts, all students were enrolled in the laboratory, where they completed *only* the two *TST Motion and Force* kinematics laboratories.[16] At both Oregon and Tufts, students were awarded a small number of points toward their final grades for attending and handing in their Prediction Sheets, but their answers were not graded.

Figure 8 compares student learning of dynamics concepts in traditional instruction to learning in identical courses with *ILDs*. As we mentioned in Sec. IV, the pre-test results for Oregon students in 1991 and Tufts students in 1994 were very similar to those of the combined 1989–1990 group of Oregon students, which we show in the first bar of Fig. 8. In comparison, the last two bars show that the effect of experiencing *about two full lectures* of *ILDs* is very substantial.

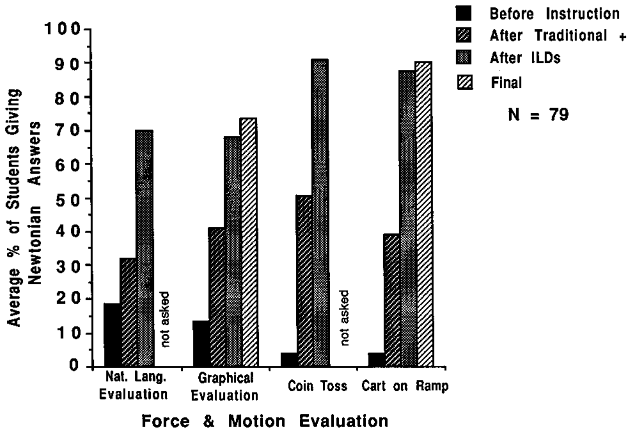

Fig. 9. Assessment history for the 1991 Oregon noncalculus NOLAB group showing understanding of dynamics before, during, and after instruction which included kinematics and dynamics *ILDs*.

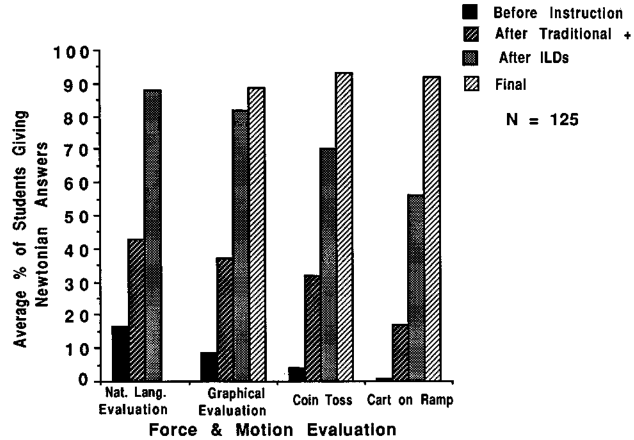

Fig. 10. Assessment history for the 1994 Tufts noncalculus course showing understanding of dynamics before, during, and after instruction which included two *TST* kinematics labs, and kinematics and dynamics *ILDs*.

VII. INSTRUCTIONAL AND ASSESSMENT HISTORIES

In order to illustrate the proper use of the FMCE in assessing the effectiveness of learning strategies and to give more detail on the experimental protocol used in this research, we present here a more detailed account of the timelines of instruction and testing at Oregon and Tufts. Figure 9 shows an assessment history for the noncalculus NOLAB group of Oregon students, while Fig. 4 shows results for the LAB group. The bars labeled ''Before Instruction'' (meaning before all dynamics instruction) show the results on the FMCE after two traditional kinematics lectures. (In all of these studies at both Oregon and Tufts, neither the evaluation questions nor the answers were returned or posted at any time until after the final examination.) After two more weeks of lectures, including several lectures on Newton's Laws, the students experienced a total of about one lecture of kinematics *ILDs*. About a week later, after all lectures on dynamics were finished, dynamics questions from the FMCE were given as part of the midterm examination. The bars labeled ''After Traditional+'' in Fig. 9 show the effect on *dynamics* conceptual understanding of enhancing *kinematics* instruction with the kinematics *ILDs*. The NOLAB students improved on the natural language questions by 14%, on the graphical questions by 24%, on the Coin Toss questions by 47%, and on the Cart on Ramp questions by 35%.

These improvements after enhanced kinematics instruction and traditional dynamics instruction can be explained by our previous research on the learning hierarchy formed by kinematics and dynamics concepts. We have shown that improving student understanding of kinematics also improves student learning of dynamics, *even if dynamics is taught in a traditional manner*.[4,5]

We have reported previously on substantial gains in conceptual understanding of kinematics by students who have experienced our active learning laboratories.[3] Our analysis was based on averages of students' responses on the four velocity and five acceleration questions on the FMCE. What about the effect of *ILDs*? Whereas at Oregon an average of only 35% of noncalculus NOLAB students can answer the acceleration questions and 70% the velocity questions correctly after traditional instruction, 80% of these same students answer the acceleration questions and 90% answer the velocity questions correctly after a combination of the two kinematics sequences of *ILDs*. For noncalculus LAB students at Oregon and for Tufts noncalculus students, both of whom also completed the two *TST* kinematics labs, these percentages rise to 90%–95% on both sets of questions.

At the time of the midterm assessment, the LAB students had also completed the four *TST Motion and Force* labs. The even larger increases seen in the bar in Fig. 4 labeled ''After TST Labs,'' have already been mentioned in Sec. V. About 70% of the LAB students are answering in a Newtonian manner.

About a week after the midterm examination, the 40 minutes of *ILDs* on Newton's First and Second laws were presented to the students. In the lecture following the *ILDs*, the same dynamics questions from the FMCE were asked as part of a quiz—with the order of questions and choices rearranged. The results on this quiz for the NOLAB group are shown by the bars labeled ''After ILDs'' in Fig. 9. Figure 4 shows the results for the LAB students. The effect of the dynamics *ILDs* on the NOLAB group seems truly remarkable in that nearly 70% are now answering both natural language and graphical questions in a Newtonian way *after only an additional 40 minutes of interactive presentation of the concepts in lecture*. Students are doing even better on the Coin Toss and Cart on Ramp questions. The LAB group also shows some additional improvement, so that now roughly 80% are answering the questions in a Newtonian way. (Since such a large percentage of the LAB group was answering these questions correctly before the dynamics *ILDs*, we expect that those who were still missing these questions were among the weakest students in the class. The fact that the *ILDs* still were effective in changing the view of dynamics for approximately half of these weaker students seems very encouraging.)

The assessment history of students in the noncalculus general physics course at Tufts in Fall, 1994 is shown in Fig. 10. One difference from Oregon was that at Tufts all traditional instruction in kinematics and dynamics was completed *before any ILDs were presented*. (The timelines at Oregon and Tufts were necessitated by our desire to assess the effectiveness of the *ILDs* independently from traditional instruction.) The ''Before Instruction'' evaluation represents results on the FMCE given on the first day of class. The students were given traditional lectures and problems on kinematics and dynamics. They also completed the first two *TST Motion and Force* labs on kinematics. After all traditional instruction on mechanics (plus the kinematics labs), the students were evaluated again. Since the kinematics instruction was enhanced by the two labs, the data are labeled ''Traditional+'' in Fig. 10.

During the next week, two 40-min sequences of *ILDs* on kinematics and Newton's First and Second Laws were presented. The day after the second set of *ILDs*, the dynamics questions with rearranged choices were included as 45 out of 100 points on the second hour exam in the course. The results are very gratifying. In Fig. 10 the bars labeled ''After ILDs'' show a gain of almost 50% from 80 min of *ILD* instruction, with almost 90% of the students answering questions in a Newtonian way after instruction enhanced by *ILDs*. The total gain of over 75% from before instruction should be compared to the 7%–10% gain we have seen resulting from traditional instruction.

VIII. RETENTION OF CONCEPTUAL KNOWLEDGE GAINED FROM ACTIVE LEARNING LABORATORIES AND *ILDs*

Retention of the Newtonian conceptual view seems to be very good for students who have completed the *TST* or *RTP* labs. Whenever questions were asked again up to six weeks after instruction in dynamics had ended, the percentage of students answering in a Newtonian way increased rather then decreased. We attribute this increase to assimilation of the concepts.

It might not be too surprising if the improved learning from the *ILDs* were more ephemeral. The research data, however, seem to show that the *ILD*-enhanced learning also is persistent. As a test of retention, the Force Graph and Cart on Ramp questions were included on the Oregon final examination. The final was given about six weeks after the dynamics *ILDs*, during which time no additional dynamics instruction took place. The bars labeled ''Final'' show the results for the NOLAB group in Fig. 9 and for the LAB group in Fig. 4. As can be seen, assimilation apparently has resulted in a 6% increase for the graphical questions and a more modest increase for the Cart on Ramp questions. The bars labeled ''Final'' in Fig. 10 show the results on the Tufts final, which was seven weeks after dynamics instruction—including *ILDs*—had ended. There is a 7% increase on the graphical questions, a 23% increase on the Coin Toss, and a 36% increase on the Cart on Ramp questions, even though there was no *additional relevant instruction*. (It should be noted that the post-test labeled ''After ILDs'' was given the next day after the dynamics *ILD*, so that there was no time for assimilation.)

IX. SUMMARY OF EVIDENCE FOR THE VALIDITY OF THE FMCE

Our observations that 70%–90% of students answer the FMCE dynamics questions from a Newtonian perspective at the end of the term after completing the *TST* or *RTP* laboratory curriculum and/or participating in the *ILDs*, while less than 20% do so after traditional lecture instruction, has led some to question the validity of the test. Are the questions significant indicators of student understanding of dynamics?

Force Questions Asked only on Final

In each of the following examples of motion of an object (1-10), choose the one description below (A - J) of the net (resultant) force on the object which could keep the object moving as described. You may use a choice more than once or not at all.

- A. The net force is in the direction of the motion and is **increasing** in strength (magnitude).
- B. The net force is in the direction of the motion and is of **constant** strength (magnitude)
- C. The net force is in the direction of the motion and is **decreasing** in strength (magnitude).
- D. The net force is **zero**.
- E. The net force is in the direction **opposite** the motion and is **increasing** in strength (magnitude).
- F. The net force is in the direction **opposite** the motion and is of **constant** strength (magnitude)
- G. The net force is in the direction **opposite** the motion and is **decreasing** in strength (magnitude).
- J. None of the net force descriptions is correct.

X ( ) ( ) Indicates Newtonian answer followed by % of students giving this answer at Oregon in 1991 and Tufts in 1994, respectively.

B (81) (92) 1. What net force will cause an automobile moving on a highway to speed up at a steady (constant) rate.

D (80) (97) 2. What net force will cause an automobile moving on a highway to maintain a constant speed of 55 miles per hour.

D (99) (95) 3. What is the net force on an ice skater gliding across a frozen lake at a constant speed.

F (95) (94) 4. A ball was thrown upward. What is the net force on the ball right after it is released and is moving upward, slowing down at a steady rate (negligible air resistance)?

B (82) (86) 5. What is the net force on the same ball as it is falling downward after reaching its highest point? (ignore any effects of air resistance)

F (82) (93) 6. An automobile moving at 55 miles per hour has the brakes applied suddenly to avoid a deer. What is the net force on the car as it slows down at a quick but steady (constant) rate?

D (54) (76) 7. What is the net force on a bicycle that is being pedaled up a hill at a steady (constant) speed?

B (91) (93) 8. What is the net force on a bicycle that is speeding up at a steady (constant) rate as it rolls down a hill?

F (89) (95) 9. A bicycle after coasting along level ground comes to a hill. What is the net force on the bicycle as it rolls up the hill slowing down at a steady (constant) rate?

F (89) (95) 10. What is the net force on an airplane as it moves down the runway slowing down at a steady (constant) rate after landing?

Fig. 11. Alternative assessment questions asked on the final exam at Oregon and Tufts which test understanding of dynamics in different contexts. The first set of numbers in parentheses show the percent of the 1991 Oregon noncalculus general physics students who had answered at least seven of the eight Force Graph questions in a Newtonian manner who also did so on these questions. The second set of numbers in parentheses shows the same percentages for the 1994 Tufts noncalculus students.

To some extent, we have already addressed important questions that might be raised. Student answers to the Force Graph questions correlate with answers to the very different format Force Sled questions which probe the same concepts. The correlation holds both before and after traditional or enhanced instruction.

To explore further the significance of the Newtonian student responses, we also included on the final exam at Oregon and Tufts a new set of simple conceptual questions which had not been asked previously. Figure 11 shows ten of these new questions which are of a different format and set in rather different contexts than the Force Graph questions. We only consider students at Oregon and Tufts who answered at least seven of the eight Force Graph questions from a Newtonian point of view. The first number in parentheses after each Newtonian answer in Fig. 11 indicates the percentage of Oregon students giving the Newtonian answer, while the second number is the percentage of Tufts students giving this answer. The results were impressive, with nine out of ten of these questions answered from a Newtonian point of view by 80% or more Oregon students and 86% or more Tufts students. The results on these new questions were particularly gratifying, since previous work had shown us that students often do not generalize in ways that seem obvious to physicists.

After traditional or enhanced instruction, students statistically answer the Coin Toss questions and the Cart on Ramp questions in a non-Newtonian way even after they answer most of the other questions on the FMCE in a Newtonian manner.[4] Many of their answers seem to indicate that they associate force with velocity rather than acceleration. As shown in Sec. III, after traditional instruction only 5% of the students at Oregon answer the Coin Toss questions in a Newtonian manner, while after the laboratories and *ILDs* at Oregon and after the *ILDs* at Tufts, over 90% do.

The Coin Toss questions and analogs provide more evi-

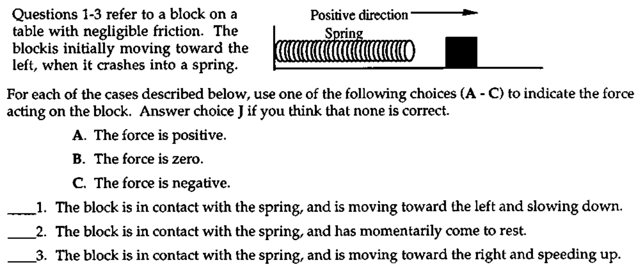

Fig. 12. Alternative coin toss analog questions asked on the final exam at Oregon in 1991 and Tufts in 1994.

dence that students who answer the Force Graph questions from a Newtonian point of view have made a fundamental belief change. If we look again at the sample of students at Oregon and Tufts who answered at least seven of the eight Force Graph questions from a Newtonian point of view, we find that 93% of these students also did so on the Cart on Ramp questions. Figure 12 shows a coin toss analog which they had not seen previously, a block sliding into a spring. Ninety-two percent of these same students again answered from a Newtonian point of view.

As with all the questions on the FMCE, students who answered correctly were also able to describe in words why they picked the answers they did.[5] Statistically one of the last questions to be answered in a Newtonian manner is the force on a cart rolling up a ramp as it reverses direction at the top (Cart on Ramp question 9). Students were asked to explain how they determined this force. The following are typical written explanations from students who answered this question from a Newtonian point of view:

> ''After the car is released the only net force acting on it is the x-component of its weight which has a net force down the ramp in the positive direction.''
>
> ''When the car is at the top of the ramp, its velocity is 0 for just an instant, but in the next instant it is moving down the ramp, v2−v1=a pos number so it is accel. down. Also, gravity is always pulling down on the car no matter which way it is moving.''
>
> ''The only two forces involved were gravity and friction. At the top of the ramp the net force was downward because gravity is higher in magnitude than friction (unless the tires & the ramp were sticky).''

Typical student answers for those who answered as if motion implies force were:

> ''At the highest point, the toy car's force is switching from one direction to another and there are no net forces acting upon it, so it is zero.''
>
> ''Because at the one instant the car is at its highest point it is no longer moving so the force is zero for that one instant it is at rest=net force=0.''

The agreement between the multiple-choice and open answer responses is almost 100%. Such results give us confidence in the significance of student choices.

In summary, most students answer the Force Graph or Force Sled questions as if they held a Newtonian point of view, and also are able to answer Coin Toss and coin toss analog questions and other questions that they have never seen before. In addition, students' written explanations agree with their choices on these multiple-choice questions. These results support the usefulness of the questions on the FMCE for evaluating student understanding.

X. WHY IS THE FMCE INSTRUCTIONALLY USEFUL?

The difficulties in convincing physics professors and high school teachers to give up course time for testing, our desire to make evaluation less subjective, and the effort involved in analyzing large samples moved us to use multiple-choice questions on the FMCE. Although a more complete understanding of student learning can be gained by an open-ended questioning process, the FMCE has allowed us to gather sufficient data at many different institutions to counter the common response that ''my students do not have these difficulties you describe.'' Almost all answers, ''right or wrong'' help us to evaluate student views about dynamics. Because the available choices in the questions were derived from students' answers to free response questions and from student interviews, students almost always find an answer that they are satisfied with. Guessing correctly is very difficult because many of the questions require students to choose an answer from up to nine choices. The correlations among questions have been examined and individual questions have been correlated with more open-ended student answers. Because we are able to identify statistically most student views from the pattern of answers and because there are very few random answers, we are also able to identify students with less common beliefs about motion and follow up with interviews or open-ended questions. The use of an easily administered and robust multiple-choice test has also allowed us and others to track changes in student views of dynamics[4,5] and to separate the effects of various curricular changes on student learning.

Student answers correlate well (above 90%) with written short answers in which students explain the reason for their choices, and almost all students pick choices that we can associate with a relatively small number of student models.[5] Testing with smaller student samples shows that those who can pick the correct graph under these circumstances are almost equally successful at drawing the graph correctly without being presented with choices.

The great majority of students at Oregon and Tufts who completed the MBL laboratory curricula and/or *ILDs* answered the FMCE dynamics questions in a Newtonian manner. It would be a mistake to imagine that students uniformly apply a consistent model (at least from the point of view of most physicists) to all ''manners'' of motion. Many students consider speeding up, slowing down, moving at constant velocity, and standing still to be independent states of motion that do not require a consistent relationship between force and acceleration or velocity. Numbers of students commonly require an object slowing down to have a constant force opposing the motion while requiring an ever increasing force for an object which is speeding up. The dynamics of these changing student views is described elsewhere.[5] The fact that most students are using ''models'' (even if they are incorrect or are applied in very limited circumstances) is a good beginning for instruction.

XI. CONCLUSIONS

We have developed and refined the research-based Force and Motion Conceptual Evaluation so that it is now a reliable means of assessing student understanding of mechanics concepts, and it is easily administered to large groups of students. Our studies of conceptual understanding using this test show that introductory physics students do not commonly understand kinematics and dynamics concepts as a result of thorough traditional instruction. Since the choices available to students on the FMCE allow us to distinguish among common student views about dynamics,[5] this test has been useful for guiding the development of instructional strategies. This research and that of others, along with the development of user friendly microcomputer-based laboratory tools, have allowed us to extend our computer supported, active learning laboratory curricula to dynamics and have allowed us to develop a strategy for more active learning of these concepts in lectures using *ILDs*. Assessments using the FMCE indicate that student understanding of dynamics concepts is significantly improved when these learning strategies are substituted for traditional ones. In a future paper we will discuss assessment of learning of Newton's Third Law in laboratory and lecture using the FMCE.

ACKNOWLEDGMENTS

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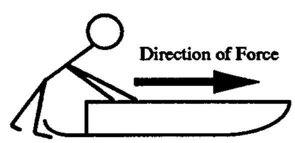
APPENDIX A: COMPLETE FORCE AND MOTION CONCEPTUAL EVALUATION

TOOLS FOR SCIENTIFIC THINKING: FORCE & MOTION CONCEPTUAL EVALUATION

<u>Directions:</u> Answer questions 1-43 in spaces on the answer sheet.

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 <u>one</u> force (A through G) which would keep the sled moving as described in each statement below.**

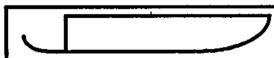
You may use a choice more than once or not at all but choose only one answer for each blank. If you think that none is correct, answer choice J.



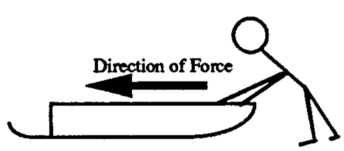
A. The force is toward the **right** and is **increasing** in strength (magnitude).

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)?

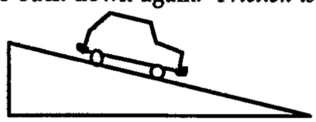
______4. Which force would keep the sled moving toward the left and speeding up at a steady rate (constant acceleration)?

______5. The sled 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)?

8-10 refer to a toy car which is given a quick push so that it rolls up an inclined ramp. After it is released, it rolls up, reaches its highest point and rolls back down again. *Friction is so small it can be ignored.*



Use one of the following choices (**A** through **G**) to indicate the **net force** acting on the car for each of the cases described below. Answer choice **J** if you think that none is correct.

- (A) Net **constant** force **down** ramp
- (B) Net **increasing** force **down** ramp
- (C) Net **decreasing** force **down** ramp
- (D) Net force zero
- (E) Net **constant** force **up** ramp
- (F) Net **increasing** force **up** ramp
- (G) Net **decreasing** force **up** ramp

______8. The car is moving up the ramp after it is released.
______9. The car is at its highest point.
______10. The car is moving down the ramp.

Questions 11-13 refer to a coin which 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 is **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.

Questions 14-21 refer to a toy car which can move to the right or left along a horizontal line (the positive part of the distance axis).

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

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

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

__14. The car moves toward the right (away from the origin) with a steady (constant) velocity.

__15. The car is at rest.

__16. The car moves toward the right and is speeding up at a steady rate (constant acceleration).

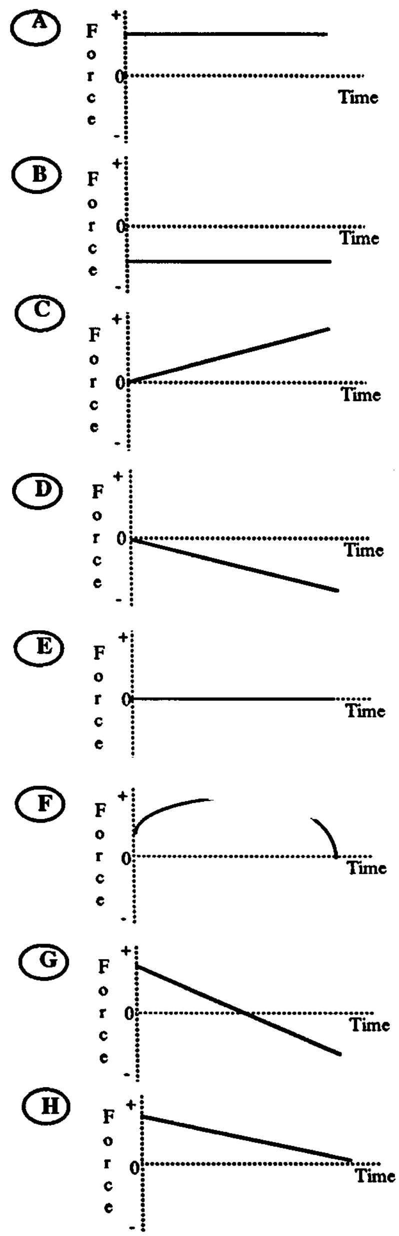
__17. The car moves toward the left (toward the origin) with a steady (constant) velocity.

__18. The car moves toward the right and is slowing down at a steady rate (constant acceleration).

__19. The car moves toward the left and is speeding up at a steady rate (constant acceleration).

__20. The car moves toward the right, speeds up and then slows down.

__21. The car was pushed toward the right and then released. Which graph describes the force <u>after</u> the car is released.

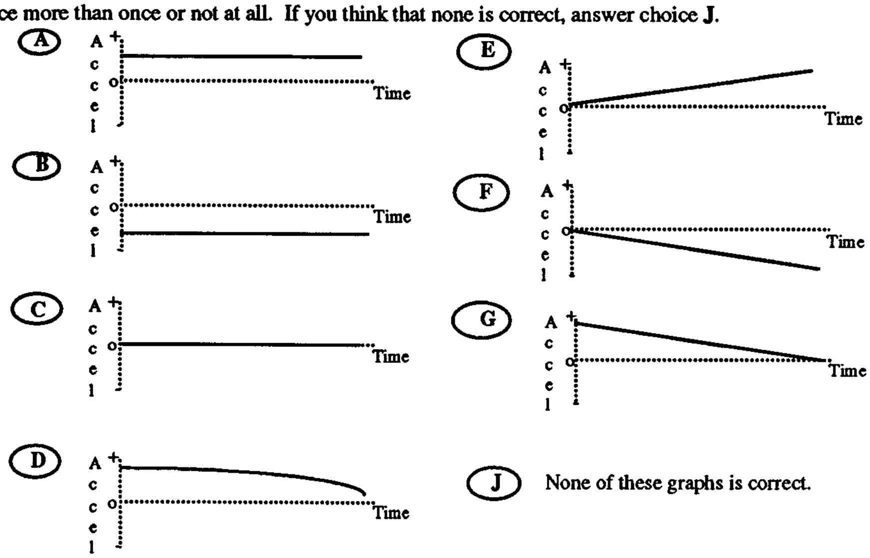


(J) None of these graphs is correct.

Questions 22-26 refer to a toy car which can move to the right or left along a horizontal line (the + distance axis). The positive direction is to the right.

Different motions of the car are described below. Choose the letter (A to G) of the **acceleration-time** graph which corresponds to the motion of the car described in each statement.

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



_____22. The car moves toward the right (away from the origin), speeding up at a steady rate.
_____23. The car moves toward the right, slowing down at a steady rate.
_____24. The car moves toward the left (toward the origin) at a constant velocity.
_____25. The car moves toward the left, speeding up at a steady rate.
_____26. The car moves toward the right at a constant velocity.

Questions 27-29 refer to a coin which 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 acceleration of the coin during each of the stages of the coin's motion described below. Take up to be the **positive** direction. Answer choice **J** if you think that none is correct.

- **A.** The acceleration is in the negative direction and constant.
- **B.** The acceleration is in the negative direction and increasing
- **C.** The acceleration is in the negative direction and decreasing
- **D.** The acceleration is zero.
- **E.** The acceleration is in the positive direction and constant.
- **F.** The acceleration is in the positive direction and increasing
- **G.** The acceleration is in the positive direction and decreasing

___27. The coin is moving upward after it is released.
___28. The coin is at its highest point.
___29. The coin is moving downward.

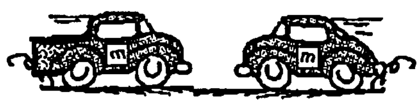
Questions 30-34 refer to collisions between a car and trucks. For each description of a collision (30-34) below, choose the one answer from the possibilities A though J that best describes the size (magnitude) of the forces between the car and the truck.

A. The truck exerts a larger force on the car than the car exerts on the truck.
B. The car exerts a larger force on the truck than the truck exerts on the car.
C. Neither exerts a force on the other; the car gets smashed simply because it is in the way of the truck.
D. The truck exerts a force on the car but the car doesn't exert a force on the truck.
E. The truck exerts the same amount of force on the car as the car exerts on the truck.
F. Not enough information is given to pick one of the answers above.
J. None of the answers above describes the situation correctly.

In questions 30 through 32 the truck is ***much heavier*** *than the car.*

_____30. They are both moving at the same speed when they collide. Which choice describes the forces?
_____31. The car is moving much faster than the heavier truck when they collide. Which choice describes the forces?
_____32. The heavier truck is standing still when the car hits it. Which choice describes the forces?

In questions 33 and 34 the truck is a small pickup and is ***the same weight*** *as the car.*



_____33. Both the truck and the car are moving at the same speed when they collide. Which choice describes the forces?
_____34. The truck is standing still when the car hits it. Which choice describes the forces?

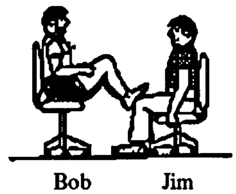
Questions 35-38 refer to a large truck which breaks down out on the road and receives a push back to town by a small compact car.

Pick one of the choices A through J below which correctly describes the size (magnitude) of the forces between the car and the truck for each of the descriptions (35-38).

A. The force of the car pushing against the truck is equal to that of the truck pushing back against the car.
B. The force of the car pushing against the truck is less than that of the truck pushing back against the car.
C. The force of the car pushing against the truck is greater than that of the truck pushing back against the car.
D. The car's engine is running so it applies a force as it pushes against the truck, but the truck's engine isn't running so it can't push back with a force against the car.
E. Neither the car nor the truck exert any force on each other. The truck is pushed forward simply because it is in the way of the car.
J. None of these descriptions is correct.

_____35. The car is pushing on the truck, but not hard enough to make the truck move.
_____36. The car, still pushing the truck, is **speeding up** to get to cruising speed.
_____37. The car, still pushing the truck, is at cruising speed and continues to travel at the **same speed**.
_____38. The car, still pushing the truck, is at cruising speed when the truck puts on its brakes and causes the car to **slow down**.

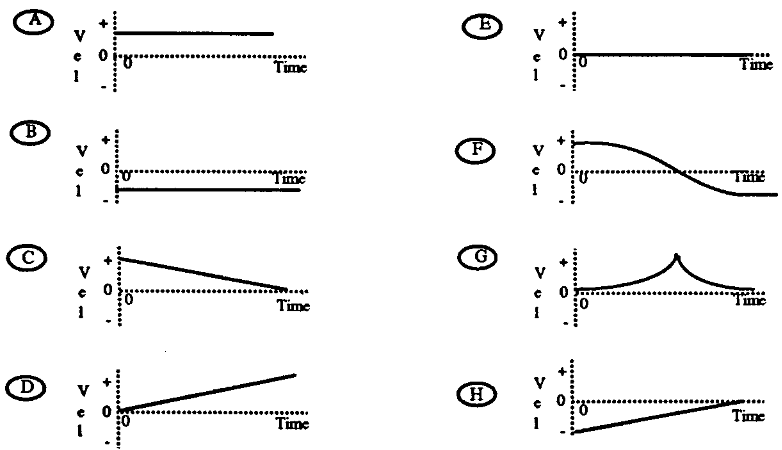
____39. **Two students sit in identical office chairs facing each other. Bob has a mass of 95 kg, while Jim has a mass of 77 kg. Bob places his bare feet on Jim's knees, as shown to the right. Bob then suddenly pushes outward with his feet, causing both chairs to move. In this situation, while Bob's feet are in contact with Jim's knees,**



A. Neither student exerts a force on the other.
B. Bob exerts a force on Jim, but Jim doesn't exert any force on Bob.
C. Each student exerts a force on the other, but Jim exerts the larger force.
D. Each student exerts a force on the other, but Bob exerts the larger force.
E. Each student exerts the same amount of force on the other.
J. None of these answers is correct.

Questions 40-43 refer to a toy car which can move to the right or left along a horizontal line (the positive portion of the distance axis). The positive direction is to the right.

Choose the correct velocity-time graph (A - G) for each of the following questions. You may use a graph more than once or not at all. If you think that none is correct, answer choice J.



J None of these graphs is correct.

___40. **Which velocity graph shows the car moving toward the right (away from the origin) at a steady (constant) velocity?**

___41. **Which velocity graph shows the car reversing direction?**

___42. **Which velocity graph shows the car moving toward the left (toward the origin) at a steady (constant) velocity?**

___43. **Which velocity graph shows the car increasing its *speed* at a steady (constant) rate?**

[1]Revisions and updates of the Force and Motion Conceptual Evaluation, as well as conceptual evaluations under development in other areas of physics, are available from the Center for Science and Mathematics Teaching, Tufts University, 4 Colby Street, Medford, MA 02155, or from the *Workshop Physics On-line Instructor Resource Guide* on the World Wide Web at http://physics.dickinson.edu.
[2]This work was supported in part by the National Science Foundation under Grant No. USE-9150589, ''Student Oriented Science,'' Grant No. USE-9153725, ''The Workshop Physics Laboratory Featuring Tools for Scientific Thinking,'' and Grant No. TPE-8751481, ''Tools for Scientific Thinking: MBL for Teaching Science Teachers,'' and by the Fund for Improvement of Post-secondary Education (FIPSE) of the U.S. Department of Education under Grant No. G008642149, ''Tools for Scientific Thinking,'' and number P116B90692, ''Interactive Physics.''
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[19] The MBL probes, interface, software, and curricula discussed here are available from Vernier Software, 8565 Beaverton-Hillsdale Highway, Portland, OR 97225-2429.
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[22] Copies of the complete mechanics *Interactive Lecture Demonstration* package, including teacher instructions and student Prediction and Results sheets are available from Vernier Software, 8565 Beaverton–Hillsdale Highway, Portland, OR 97225-2429.