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USING THE RESULTS OF RESEARCH IN SCIENCE EDUCATION TO IMPROVE SCIENCE LEARNING

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ABSTRACT

Traditional science instruction in the United States, refined by decades of work, has been shown to be largely ineffective in altering student understandings of the physical world. Even at the university level, students who take physics courses, whether they be science majors or not, enter and leave the courses with fundamental misunderstandings of the world about them essentially intact: their learning of facts about science remains within the classroom and has no effect on their thinking about the larger physical world. There is evidence that listening to someone talk about scientific facts and results is not an effective means of developing concepts. The evidence shows that students of all ages learn science better by actively participating in the investigation and the interpretation of physical phenomena and that well-designed computer-based pedagogical tools that allow students to gather, analyze, visualize, model and communicate data can aid students who are actively working to understand science.

In the United States, the benefits of widespread science literacy for non-scientists have been well and eloquently argued. There has been extensive discussion, with some agreement, of the knowledge and skills a person should have to be science literate.(1) Unfortunately less attention has been paid to successful methods of teaching and learning science. There is evidence that traditional methods of teaching science are unable to bring a majority of students, even those intending to become scientists, to understand the physical world. When these traditional methods are used with future teachers, ineffective teaching methods are modeled and often propagated without change. Here I will focus on the teaching and learning of physics as an example. The techniques and methods described also apply to the teaching and learning of other sciences.

WHY DON’T STUDENTS UNDERSTAND PHYSICS? (2)

Are most students in physics courses acquiring a sound conceptual grasp of basic physics principles? For many years physicists teaching introductory courses have believed that they are, but those doing research in physics education have been convinced that they are not. Recently, extensive studies of students' basic conceptual knowledge before and after introductory physics courses in high schools and colleges have convinced some in the larger community of physics teachers that there is less basic understanding than they had believed. The results of these studies show that students in selective universities, whether they be science majors or not, fail to agree with physicists when they answer the simplest conceptual questions. These same students are able to solve many traditional problems involving the solution of algebraic equations or even those requiring the methods of the calculus. Even so, these students enter and leave the courses with fundamental misunderstandings of the world about them essentially intact: their learning of facts about science remains within the classroom and has no effect on their thinking about the larger physical world.

So it seems that traditional science instruction in the United States, refined by decades of work, has been shown to be largely ineffective in altering student understandings of the physical world. The ineffectiveness of these courses is independent of the apparent skill of the teacher, and student performance does not seem to depend on whether students have taken physics courses in secondary school.

Effective science education results in citizens who are scientifically literate and better able to make informed decisions about issues involving science and technology that effect their present lives and the lives of future generations. There are a number of barriers to an effective science education for non-scientists, as well as for potential scientists, and especially for future teachers of science. Students often perceive science as difficult, boring, and overly concerned with detail. This is due in part to stereotypes and in part to the courses actually taught. Science is exciting to scientists because they are engaged in discovery and in creatively building and testing models to explain the world around them. Yet scientists rarely *preach what they practice*. Science courses rarely reflect the practice of science. In most courses, students do not "do" science. Instead they only hear lectures about already validated theories. Not only do they not have an opportunity to form their own ideas, they rarely get a chance to work in any substantial way at applying the ideas of others to the world around them. The worst courses consist of the presentation of collections of unrelated science facts and vocabulary with no attempt to develop critical thinking or problem solving skills.

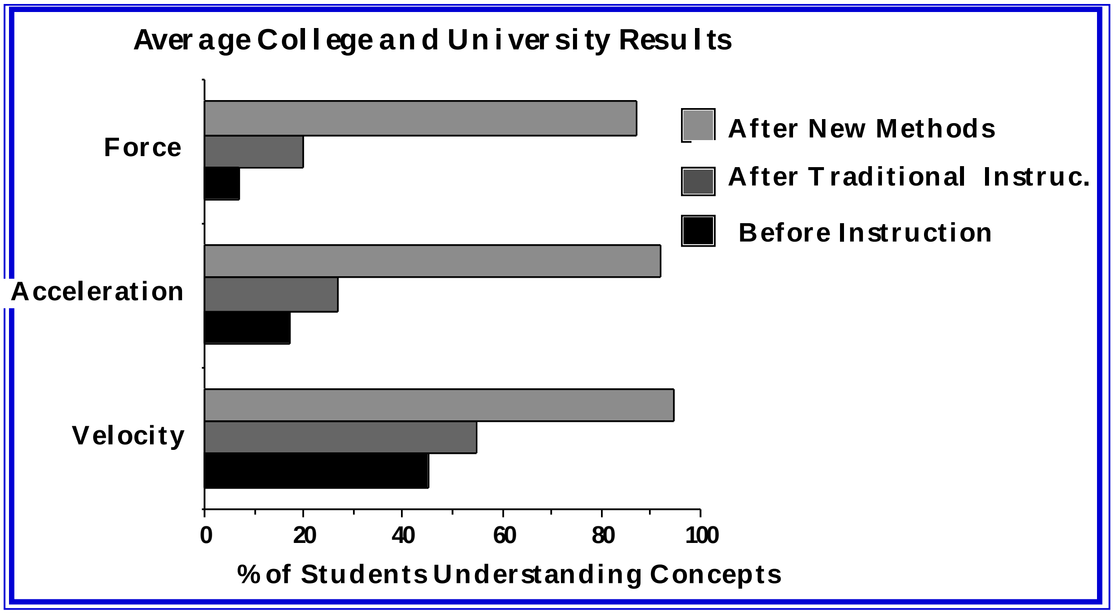


Figure 1-Composite data on student understanding of kinematics (labeled **Velocity** and **Acceleration** concepts) and dynamics, force and motion as described by Newton's Laws (labeled **Force** concepts). Dark bars show student understanding coming into beginning university courses, striped bars are after all traditional instruction. While the percentage of students who know concepts coming in can vary with the selectivity of the university, the effect of traditional instruction is to change the minds of only 7 to 15% of students. New methods described later in this paper result in approximately 90% of students understanding concepts (lighter solid bars). (Students evaluated using the *Force and Motion Conceptual Evaluation.*)

Consider traditional instruction in dynamics, force and motion, as an example of student conceptual learning in physics. Although a Newtonian framework is essential to understanding non-relativistic (and later relativistic) motion, it is common for more than 80% of students to answer most questions from a non-Newtonian point of view after an introductory physics course. Such students may believe, for example, that a net force is required to keep an object in motion at a constant velocity, that there is a residual force on an object that has been pushed and released that keeps it moving, and that acceleration must increase as velocity increases. In contrast, students and physicists who believe the world behaves in a Newtonian manner (for every day speeds) use a conceptual framework based on Newton's laws of motion. They understand that a body moving at constant velocity requires no net force to keep it moving and so no residual forces are required. They also understand that a constant acceleration produces a uniformly increasing velocity. Learning to substitute values into the equations of motion seldom results in Newtonian conceptual understanding. Research has shown that standard instruction commonly changes the conceptual point of view of 5 to 15% of the students in the area of dynamics (force and motion). Figure 1 shows the results of composite research data for thousands of students at universities who took the *Force and Motion Conceptual Evaluation*. (4)

Such results do not only apply to the United States. Research done at the University of Sydney in Australia, again using the *Force and Motion Conceptual Evaluation*, shows that students entering the university are better prepared than many students in the US and more believe the Newtonian model before university instruction. However, good traditional university instruction again results in only an additional 10% of students adopting the Newtonian model for force and motion.

The failure of beginning physics courses to convince students that the Newtonian view of motion makes more sense of the world than their fragmentary, childhood views, has broader implications than the fact that the students do not understand force and motion. It calls into question, particularly for students not intending to become scientists, the validity of the scientific process. If science does not make "sense" for students, then there is no good reason to accept conclusions arrived at through the process of science. Of course some will "accept" science merely on the perceived authority of scientists without any expectation of understanding it. Such a result is clearly not desirable and will also be a severe problem for future teachers.

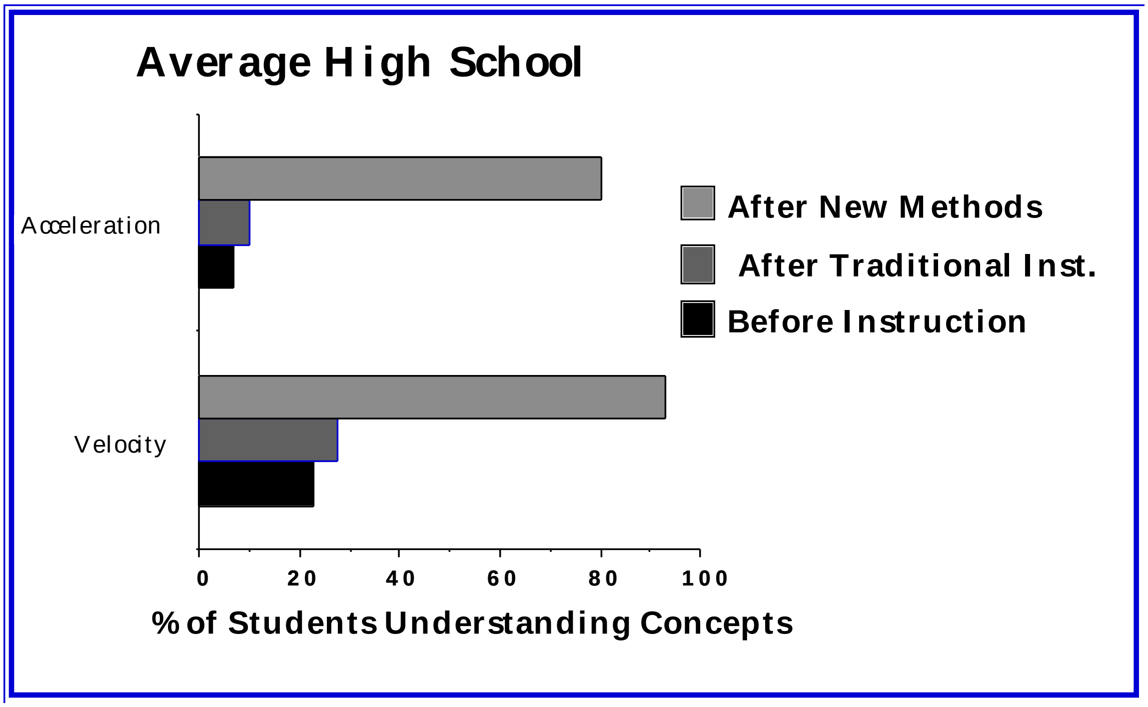


Figure 2-Composite data on student understanding of kinematics (labeled **Velocity** and **Acceleration** concepts). Dark bars show student understanding coming into physics courses in high schools, striped bars are after all traditional instruction. While the percentage of students who know concepts coming in can vary with the location of the high school, the effect of traditional instruction is to change the minds of approximately 10% or less of the students. New methods described in text result in 80 to 90% of students understanding concepts (lighter solid bars). (Students were evaluated using the *Force and Motion Conceptual Evaluation*)

If university instruction is changing the conceptual ideas of only 10% of the students, what is happening in high schools? Figure 2 shows composite results for US high schools which are similar to university results shown in Figure 1. Note that students in even an average high school who use the new methods described below, learn concepts much more successfully than university students who experience well-presented traditional instruction at a selective university.

There is more widespread agreement on the ineffectiveness of traditional instruction than there is on the solutions to the problems of traditional instruction. For some time, substantial agreements among researchers in physics education on the ways that traditional instruction is not working have been masked by real and apparent disagreement over particular ways of defining physics learning and over disagreements about the appropriate pedagogical response. Such disagreement has too often meant that much work in research and pedagogy goes on as a series of separate efforts, so that projects with the potential to have widespread impact on physics teaching and learning remain isolated. What is needed to change the state of physics education is agreement on a set of underlying principles about the teaching and learning of physics that will support the integration of the work of many different groups into a coherent educational response based on careful research and with the potential to influence the larger physics and science community.

A GROWING CONSENSUS ON THE PRINCIPLES FOR A NEW SCIENCE PEDAGOGY.

Some researchers in physics education from the United States formed the New Mechanics Advisory Group at Tufts University in 1992 to order to examine student learning in physics. The researchers came to agreement on the following generalizations about student learning in physics and the inadequacies of traditional instruction (These were originally drafted by Lillian McDermott):

- Facility in solving standard quantitative problems is not an adequate criterion for functional understanding.
- A coherent conceptual framework is not typically an outcome of traditional instruction. Rote use of formulas is common.
- Certain conceptual difficulties are not overcome by traditional instruction.
- Growth in reasoning ability does not usually result from traditional instruction.
- Connections among concepts, formal representations (algebraic, diagrammatic, graphical), and the real world are often lacking after traditional instruction.
- Teaching by telling is an ineffective mode of instruction for most students.

Each generalization is supported by research from different sources using different techniques. These sources include, for example, the Physics Education Group at the University of Washington (3), which elicits detailed accounts of student understanding through interviewing; the analysis done by the Center for Science and Mathematics Teaching at Tufts University on responses from thousands of students in introductory physics courses at many different institutions to short-answer questions which are part of the *Force and Motion Conceptual Evaluation* (4, 5); and the work done by David Hestenes at Arizona State University in developing benchmark conceptual exams. (6)

Each of the generalizations about student learning has strong implications for changing physics teaching. It will be difficult for scientists who look at the evidence and who accept these results to find justifications for continuing to teach in a traditional manner. But what is a teacher to do? Even physics education researchers have disagreements about the "best" way to proceed. While most believe that students must be intellectually engaged and actively involved in their learning and that traditional instruction is failing to provide a context in which a majority of students can learn, there is more debate about which methods of teaching and what learning contexts will help students learn most effectively. Can educational technology improve physics learning? Under what conditions does collaborative learning work well? What role should experimentation play in student learning?

While the New Mechanics Meeting only articulated agreements about traditional student learning in physics, its individual members have been involved in developing new pedagogical approaches that respond to the concerns. For example, an earlier, international meeting of physicists and physics education researchers at a NATO Advanced Study Workshop addressed *STUDENT DEVELOPMENT OF PHYSICS CONCEPTS: THE ROLE OF EDUCATIONAL TECHNOLOGY*. The workshop was organized by Robert Tinker and the author and was held at the University of Pavia in Italy during 1989. The participants included researchers from nine different countries and some members of the New Mechanics Advisory Group. The participants were researchers in physics and science education and included major developers of curriculum and pedagogical tools for the teaching of students and teachers. Many of the participants were interested in incorporating recent findings in physics education research and cognitive psychology into new instructional models made possible by the use of interactive technologies.

The NATO workshop was concerned with student conceptual learning and the pedagogical uses of interactive educational technologies in physics teaching and learning. One major focus was on the uses of technologies that allowed students to construct physics concepts successfully from their own experiences of the physical world. Some of the interactive educational technologies demonstrated and discussed at the conference were real-time, computer-based, data-logging tools (often called microcomputer-based laboratory or MBL tools); the use of robotics for teaching science concepts; interactive video disk/CD ROM systems; student-directed pedagogical software tools; telecommunication as a means for students to share scientific discoveries; and constructivist intelligent tutor systems.

After examining the evidence, participants were in substantial agreement that students of all ages learn science better by actively participating in the investigation and the interpretation of physical phenomena; that listening to someone talk about scientific facts and results was not an effective means of developing concepts; and that well-designed pedagogical tools (generally computer-based) that allow students to gather, analyze, visualize, model and communicate data can aid students who are actively working to understand physics. In particular, there was evidence from a number of countries (Italy, Germany, UK, USA, Russia) that real-time Microcomputer-Based Laboratory tools in appropriate learning environments resulted in successful student learning of physics concepts. It was also agreed that to best develop their understanding, students need the freedom and ability to pursue interesting scientific investigations; the opportunity to interact with their fellow students; and the means to communicate their findings. (Unfortunately most introductory courses have none of these features.)

The international NATO Workshop resulted in substantial agreement on ways physics teaching can be changed to improve student learning. These conclusions have subsequently stood the test of time and research. The New Mechanics meeting at Tufts, in addition to building agreement about student physics learning, also began the work of refining curricular and instructional strategies that will help introductory physics students acquire a conceptual understanding in one specific area of the curriculum--Newton's Laws of Mechanics. The results of this meeting, including a revision of the dynamics sequence described by Arnold Arons in Chapter 2 of his book A Guide to Introductory Physics Teaching, were incorporated by the Activity Based Physics Group into the curricular project, *RealTime Physics: Active Learning Laboratories in Mechanics* (7) and into major revisions of the *Workshop Physics* (8) and *Tools for Scientific Thinking* (9) curricula. Extensive research on learning, which is part of these projects, is helping to establish productive instructional techniques and sequences that work for almost all introductory physics students including future teachers. Such materials are also effective in workshops for current teachers to enhance their mastery of science concepts that new standards call upon them to teach.

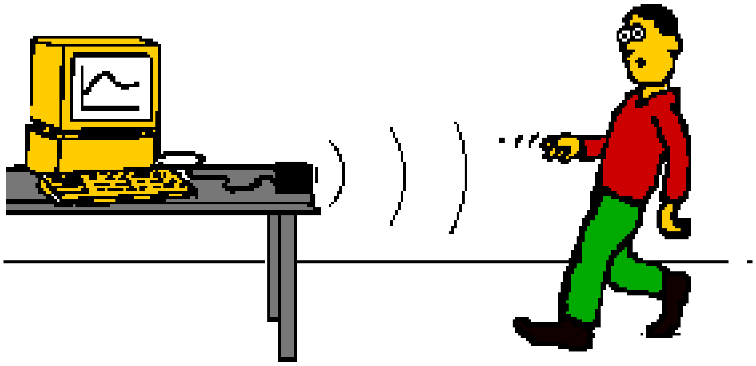


Figure 3-Student walking in front of an ultrasonic motion detector while his position is being graphed as he moves. The context and importance of this simple activity is described in the text.

EXAMPLE CURRICULAR ACTIVITIES USING NEW PEDAGOGY

Consider a simple activity that is included in all three of the activity-based, computer-assisted, guided-inquiry curricula discussed above. At the beginning of their study of motion, students first explore position, velocity and acceleration concepts using real-time graphs of body motions. This activity is effective for children in grade 4, but even in the university students are asked to walk in front of a "motion detector" that displays a graph of their position, velocity, and/or acceleration as a function of time as they move. They generally work in groups of three, are required to make predictions of experimental outcomes, and are encouraged to discuss with other group members the graphs resulting from their movements. Students answer simple conceptual questions as they work that have them describe motion verbally, in standard written language, graphically, quantitatively, and in vector representations.

What effective practices for teaching science does this example embody? In terms of general course structures we have found student learning is improved when we

- Use peer instruction and collaborative work.
- Keep students actively involved. Use activity-based guided-inquiry curricular materials.
- Use learning cycles with predictions.
- Let the physical world be the authority.
- Evaluate student understanding.
- Make appropriate use of technology.

All of the above are illustrated in this example. In terms of recommended general course content for teaching science, this example illustrates the following.

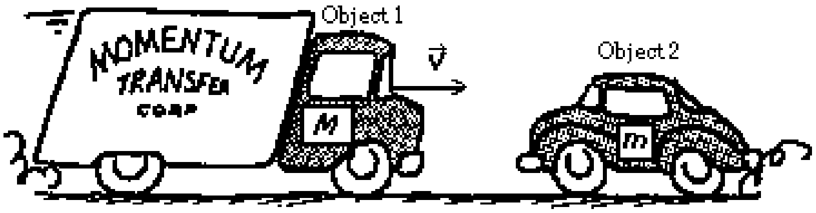
- Find answers from the physical world. (Experiment!) The "text" for science is the physical world.
- Emphasize conceptual understanding.
- Establish a conceptual foundation. Begin with what students understand. Science is generally hierarchical and students who do not learn fundamentals rarely learn more advanced concepts. (10)
- Link abstractions to the concrete. Linking graphs (an abstraction) to actual physical motion aids understanding. In this case there is also linking to the kinesthetic.
- Aid students to learn and link different representations and depictions. A graph of a physical quantity over time is a "narrative," It tells a story. Students are asked to express this narrative in verbal and written natural language. They are also asked to extract speed from position-time information by considering rates of change.
- Begin with the specific and move to the general.

Small interactive groups working with computer-assisted data gathering are certainly not possible in all learning contexts. We have developed a method to change a classroom or a lecture hall with a single computer into a more active learning environment. The *Tools for Scientific Thinking* computer-supported *Interactive Lecture Demonstrations* (4,5,11) consist of a sequence of simple experiments (6 to 8 per session) based on research of the conceptual foundation needed to learn a particular topic area in physics. The computer is equipped with data logging software, an interface and appropriate probes (MBL) for the topic area. For force and motion, we might use a force probe and a motion detector with low-friction carts to explore the result of various forces on the carts' motion. To examine the interaction forces in a collision between two objects, we would use two force probes. Figure 4 shows such an arrangement. An experiment where one cart is much heavier than another is part of the Newton's Third Law *Interactive Lecture Demonstration* sequence. The actual result of such a collision is shown in Figure 5.

In an *Interactive Lecture Demonstration* session students are given a "prediction sheet"with space to write predictions and answer questions. The sheet is collected to encourage participation. They are also given an essentially identical "results sheet" which they may fill out with the actual experimental results and keep. For each simple experiment or demonstration in the sequence, we use the following protocol.

1. Describe the demonstration and do it for the class without MBL measurements.
2. Ask students to record individual predictions.

3. Have the class engage in small group discussions with nearest neighbors.
4. Ask each student to record final prediction on handout sheet (which will be collected).
5. Elicit predictions & reasoning from students.
6. Carry out the demonstration with MBL measurements displayed.
7. Ask a few students to describe the result. Then discuss results in the context of the demonstration. Ask students to fill out “results sheet” which they keep.
8. Discuss analogous physical situations with different "surface" features. (That is, a different physical situation that is based on the same concept.)



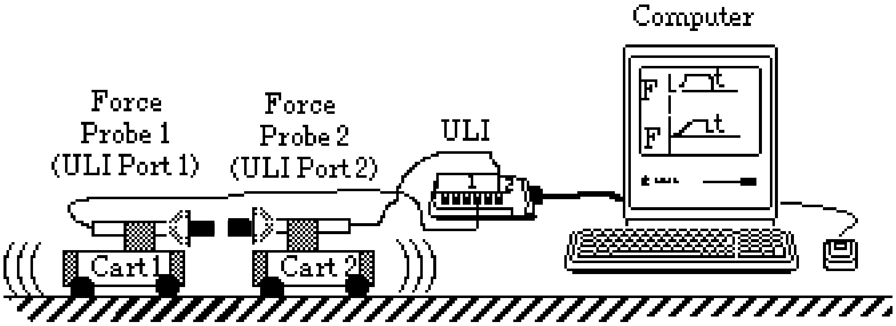


Figure 4- Arrangement for one of the experiments in Newton’s Third Law *Interactive Lecture Demonstration* sequence. The force probes measure the interaction forces between the carts. An actual result of such an experiment is shown in Figure 5.

The *Interactive Lecture Demonstrations* have resulted in substantial student conceptual learning (4,5) and students much prefer these methods to listening to lectures. These methods embody many of the same successful teaching and learning practices described above.

LEARNING RESULTS

The successes of the curricula and methods described above illustrate the possibility of large learning gains in introductory courses through the use of new methods developed through educational research. For example, the *Tools for Scientific Thinking* guided-inquiry conceptual labs are based on research on what students know; make use of real-time data collection and display (MBL); and encourage students to work collaboratively. By introducing such labs into otherwise conventional introductory courses, it is possible to help students to aline their beliefs about the physical world with those held by physicists. After traditional instruction, over 1200 students in calculus-based physics courses at five different universities, only 30% understood fundamental acceleration concepts. When, for the first time, two *Tools for Scientific Thinking* active-learning kinematics labs were offered at these universities, more than 75% of students understood these concepts. At universities where there is more experience with the labs, such as the University of Oregon and Tufts University, even in non-calculus introductory courses, 93% of students understand these concepts. At such universities, less than 15% of students held a Newtonian point of view after traditional instruction in dynamics, while 90% did so as after only two additional conceptual labs on dynamics. There is good evidence that this conceptual understanding is retained. The *Tools for Scientific Thinking* computer-supported *Interactive Lecture Demonstrations* (4,5,11) have had similar success in changing the large lecture environment into an interactive environment that invites students to learn force and motion concepts. Such limited implementation of new methods is not enough, but begins to address the problem of changing instruction in traditional environments. Similar positive results are achieved in the more comprehensive Workshop *Physics* program (8) at Dickinson College which has replaced lectures with a combination of student-oriented activities using similar active learning techniques and the educational technology described above.

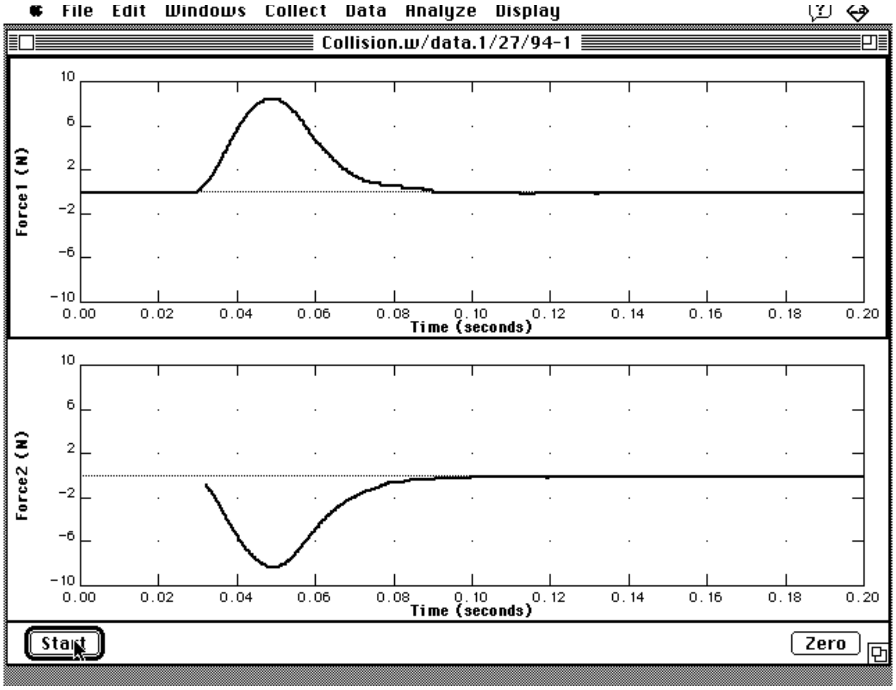


Figure 5- Actual result for one of the experiments in Newton’s Third Law *Interactive Lecture Demonstration* sequence shown in Figure 4. In this case, cart 1 is three times heavier than cart 2 but just as Newton would predict, the interaction forces are equal and opposite.

CONCLUSION

In summary, there is considerable evidence collected by researchers in physics teaching and learning that traditional instructional methods, largely lecture and problem solving, are not effective methods for promoting student learning in physics. There is also widespread, but not total, acceptance by researchers of evidence that interactive learning methods, some of which are mentioned above, work well in many different environments. There is enough agreement among careful researchers that the science teaching community would do well to use curricula and methods based on the practices that have actually been demonstrated to enhance student learning. It is also prudent to examine in a scientific way the learning results of these new methods in specific learning contexts. Initial results show that activity-based, computer-supported, interactive learning environments will well serve the diversity of students studying science.

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