New Physics Teaching and Assessment:
Laboratory- and Technology-Enhanced Active Learning

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Active learning, which integrates experimental work, plays an important role in helping students create cognitive links between the world of mathematics and that of physics. We believe that teachers and students need to incorporate active learning, hands-on activities, and visualizations in the teaching and learning of scientific phenomena and processes, especially when dealing with abstract concepts such as electromagnetism.

For more than half a decade, two universities—North Carolina State University and Massachusetts Institute of Technology—have been engaged in reforming their introductory physics courses. This chapter describes the instructional objectives that formed the basis of our reform efforts. After showing how revising the content led to a redesign of the classroom space, we set forth some of the new instructional activities that resulted from our efforts. Finally, we present and discuss the different types of assessments that were used to evaluate the efficacy of our changes.

Motivation

The underpinning of our efforts to reform the introductory calculus-based physics classes at our two institutions emanated from students' lack of interest in the subject matter and an accompanying high failure rate. Science and engineering education research indicates that students need to be engaged in the material they are studying. Hake (1998) illustrated clear differences in performance between traditional and interactive classes. Cummings et al., (1999) described and analyzed the first model of studio physics. Mazur (1997) presented his reasoning and method for increasing his students' engagement with his lectures. Of course, this idea is not confined to just the teaching of physics. Engineering has probably made the most progress toward studying and implementing "engaging" instruction. Smith, et al., (2005) outline the history of implementing active engagement and describe the research behind the pedagogy. In particular, they cite Astin (1993), who summarized data from more than 27,000 students enrolled at 309 different colleges. Austin found that interaction—among students and between students and faculty—had a much greater impact on college success, as measured on a variety of scales, than any other aspect of students' college experiences.

The book "How People Learn," (Bransford, Brown & Cocking, 1999) and its recent sequel, "How Students Learn" (Donovan & Bransford, 2005) provide a useful framework for instruction in the classroom. Basically, they propose four interconnected perspectives on learning environments: learner-centered, knowledge-centered, assessment-centered, all being enveloped by the community. Effectively designed learning environments incorporate all four perspectives. While these approaches relate to learning in general, several methods have been developed that focus specifically on teaching physics in undergraduate courses (Laws, 1997; McDermott et al., 1996; McDermott, Shaffer, et al., 2002; Sokoloff, & Thornton, 1997; Steinberg, Wittmann, & Redish, 1997). The pedagogy we describe was developed with these ideas in mind.

Augmenting the altruistic "we want our students to learn more" motivation are external pressures. Administrators respond to student and faculty complaints when prerequisite classes are reported to be poor preparation for later work. There can be considerable persuasion applied by accrediting agencies. For us, the Accrediting Board for Engineering and Technology (ABET) had great import. Their newest criteria are quite different than those of the past. For example, there are no specific science course requirements. In fact, if it can be shown that engineering program graduates are able to "apply knowledge of science," whatever that might mean, it doesn't matter how they acquired that ability. Few engineering departments want the responsibility of teaching physics, but they could take it upon themselves if they decide that is the best plan of action. Thus it behooves physics departments to make a concerted effort to provide courses that are easily related to the ABET criteria (http://www.abet.org/forms.shtml).

These criteria, besides their open-endedness, focus on teamsmanship (teamwork) and communication as well as experiments' design and problem solving. Although these have supposedly always been important, engineering schools must now rigorously demonstrate that students indeed have these skills.

NCSU Mechanics and Electromagnetism Courses – Objectives and Settings

The internal and external pressures may seem burdensome to physics instructors, but having these constraints actually makes course design easier since the "target" has been clearly specified. The NCSU effort is called SCALE-UP—Student-Centered Activities for Large Enrollment Undergraduate Programs. The SCALE-UP guidelines at NCSU that were developed for the two semester calculus-based introductory physics course are shown in Table 1. The first semester deals with Mechanics and the second – with Electromagnetism.

I. Students should develop a good functional understanding of physics. They should be able to:

- describe and explain physics concepts, including knowing where and when they apply
- apply physics concepts when solving problems and examining physical phenomena
- apply concepts in new contexts (transfer)
- translate between multiple-representations of the same concept, for example: between words, equations, graphs, and diagrams
- combine concepts when analyzing a situation.
- evaluate explanations of physical phenomena

II. Students should begin developing expert-like problem solving skills. They should be able to:

- satisfactorily solve standard textbook exercises
- apply all or part(s) of the GOAL expert problem-solving protocol in any context
- solve more challenging problems, including:
    - context-rich ("Real World") problems
    - estimation problems
    - multi-step problems
    - multi-concept problems
    - problems requiring qualitative reasoning
- evaluate other people's written solutions and solution plans

III. Students should develop laboratory skills. They should be able to:

- interact with (set up, calibrate, set zero, determine uncertainty, etc.) apparatus and make measurements

- explain the underlying physical principles of the operation of the apparatus, measurements, physical situation being studied and analysis of data
- design, execute, analyze, and explain a scientific experiment to test a hypothesis
- evaluate someone else's experimental design

IV. Students should develop technology skills. They should be able to:

- use simulations to develop mathematical models of physical situations
- utilize a spreadsheet to graph and do curve fitting
- find information on the web
- use microcomputer, video, and web-based software and hardware for data collection and analysis

V. Students should improve their communication, interpersonal, and questioning skills. They should be able to:

- express understanding in written and oral forms by explaining their reasoning to peers
- demonstrate their knowledge and understanding of physics in written assignments
- discuss experimental observations and findings
- present a well-reasoned argument supported by observations and physical evidence
- evaluate oral arguments, both their own and those espoused by others
- function well in a group
- evaluate the functioning of their group

VI. Students should develop attitudes that are favorable for learning physics. They should:

- recognize that understanding physics means seeing the underlying concepts and principles instead of focusing on knowing and using equations
- see physics as a coherent framework of ideas that can be used to understand many different physical situations
- see what they are learning in the classroom as useful and strongly connected to the real world
- be cognizant of the scientific process/approach and how to apply it
- indicate a willingness to continue learning about physics and its applications
- see themselves as part of a classroom community of learners

Table 1. NCSU objectives for the two-semester introductory physics sequence.

The objectives in Table 1 are behavior oriented, i.e., they are written in terms of specific actions students should be able to complete after instruction of the entire two-course sequence.

There are more detailed behaviors, primarily in the content areas that refer to each course and even down to the particular topical area. Creating objectives in this manner not only makes it easier for faculty and students to stay focused on the important parts of the course, but also makes assessment simpler.

Starting from a set of objectives that specified skills like communication and teamsmanship suggested that a complete redesign of the learning environment might be needed. After experimenting with different seating geometries, we discovered that round tables (6 or 7 feet in diameter) were best at facilitating discussions between students and with instructors. We place three teams of three students at each table. The teams are structured to be heterogeneous within groups, but homogeneous across groups. This ensures that students at all ability levels work together and learn from each other. We also structure the activities so that the stronger students want to help their teammates learn the material and weaker students feel a responsibility to do the best job they can.

A typical class will have students working on a series of activities. Brief periods of lecture, often less than 10 minutes, are interspersed with "tangibles" and "ponderables." The first type of activity involves hands-on observations or measurements, i.e., students work with something tangible. For example, early in the semester we ask students to find the thickness of a single page from their textbook. They then use the result to measure the diameter of a period at the end of a sentence in the book. Students invariably start by dividing the estimated or measured thickness of a large stack of the pages by the number of sheets of paper in the stack. Although they usually don't think of it in these terms until prompted, the reason for using many sheets at once is to increase the number of significant digits in the final answer. In a Socratic dialog, students are asked questions about why they tackled the problem as they did. This is often done by having them consider what answers they would have gotten from a different approach. By recognizing for themselves how significant figures play a role in a measurement, they are much more likely to continue to consider the uncertainty in their measurements throughout the course.

Ponderables are problems and calculations for interesting, complex situations. For example, we ask them: "How far does a bowling ball travel down the lane before it stops skidding and is only rolling?" No other information is given, so students need to decide what parameters need to be estimated. The insight students gain into what happens to the frictional force when skidding stops and pure rolling begins makes it worth the effort. In some cases, ponderables involve programming in VPython. The computer activities are designed to promote a view of physics as a powerful way to understand situations using just a few fundamental principles. For example, early in the semester students write a simulation of an extra-solar planetary system. A few weeks later they make minor changes to their program and use it to simulate the Rutherford alpha particle experiment where atomic nuclei were discovered. The students note that a huge range of scale, from stellar to sub-atomic dimensions, can be accurately modeled with the same physical principles.

MIT Electromagnetism Course – Objectives and Settings

The TEAL—Technology Enabled Active Learning Project at MIT is similar to the NCSU Scale-Up effort, and the MIT effort was motivated by observing the NCSU effort in its early years. The two classrooms at MIT for teaching in this format have 12 tables, each 7 feet in diameter, with each table accommodating three groups of three students, chosen heterogeneously within the group. In addition to the motivations discussed above, an additional factor in moving to an interactive engagement format at MIT was that the mainline introductory physics courses have not had a laboratory component for over 30 years, and we wanted to reintroduce a laboratory component into these physics courses (Dori & Belcher, 2005A).

The TEAL Project began with two prototype courses (about 170 students each) in electromagnetism in Fall 2001 and Fall 2002, and moved to the large mainline course (550 students) in electromagnetism in Spring 2003. A similar effort in mechanics was taught in prototype form in Fall 2003 and Fall 2004, and in the large mainline course in Fall 2005. We discuss here the course in electromagnetism, since that is the more mature course with more extensive assessment. The majority of the students in the MIT introductory physics courses are engineering majors, and thus the objectives for the courses are broadly speaking the same as listed in Table 1 for NCSU. Grades in the TEAL courses are not curved. Because collaboration is an element, it was important the class not be graded on a curve, either in fact or in appearance, to encourage students with stronger backgrounds to help students with weaker backgrounds. Also, the cut-lines in the course were set in such a way that a student who consistently did not attend class could not get an A. This was a deliberate policy to encourage attendance, based on the belief that one of the reasons for the traditionally high failure rates was the lack of student engagement with the course, as reflected by the low attendance toward the end of the term in the lecture format (typically 40%).

Despite the fact that the Spring 2003 learning gains were excellent compared to the standard lecture recitation format (see the discussion below), student acceptance of the new teaching format in Spring 2003 was mixed. To improve this acceptance, in subsequent terms we have done more training of students in collaborative methods (e.g. group work), and more extensive training for course teaching staffing in interactive engagement methods. We also increased the number of course teaching staff and perform fewer experiments that are better integrated into the course material. We also rearranged individual classes to break our active learning sessions into smaller units that can be more closely overseen by the teaching staff. Extensive course material for the Spring 2005 version of the electromagnetism course can be found on the MIT OpenCourseWare site (http://ocw.mit.edu).

A unique feature of the TEAL learning environment is the large component centered on active and passive visualizations of electromagnetic phenomena (Dori & Belcher, 2005B; See Barak, this volume). This is especially important in electromagnetism because students have a hard time connecting the abstract mathematics of vector fields to their everyday experience. The TEAL visualization approach is designed to help students visualize, develop better intuition about, and develop better conceptual models of electromagnetic phenomena. In the TEAL environment we incorporated advanced 2D and 3D visualizations to enable students get a deeper view of the nature of various electromagnetism phenomena. Such visualizations allow students to gain insight into the way in which fields transmit forces by watching how the motions of objects evolve in time in response to those forces. They also allow students to intuitively relate the forces transmitted by electromagnetic fields to those transmitted by more familiar agents, for example, rubber bands and strings. This makes electromagnetic phenomena more concrete and more comprehensible, because it allows the students to apply electromagnetic stresses to other phenomena that they already understand. These visualizations are freely available for non-profit educational use on the MIT OpenCourseWare site.

We exemplify the usefulness of the TEAL desktop experiments and Java3D visualizations through the Faraday's Law desktop experiment done in class and its corresponding visualization. In the desktop experiment, the student moves a loop of wire along the axis of a strong rare earth magnet and measures the resultant eddy current in the loop using a computer interfaced to a current probe. In the associated Java applet (a virtual reconstruction of the real desktop experiment), the student can perform the same experiment and “see” both the eddy current in the ring and the effects of the additional magnetic field it produces on the total magnetic field. The field of the eddy current is generated in accord with Lenz’s Law—that is, the field is such as to try to keep the total magnetic flux through the wire loop from changing. In the virtual experiment (in contrast to the real experiment), the student can run the virtual resistance of the wire loop down to zero. He/she then can see that in this limit no magnetic field lines can cross the radius of the loop (e.g., the flux through the loop is constant), regardless of where the student moves the loop or how fast the student moves the loop. This simulation is a visceral (although virtual) example for the student of what Lenz’s Law means, that complements (but does not replace) the real experiment. Figure 1 shows the visualization of the magnetic field configuration around the ring as it moves past the magnet.The current in the ring is indicated by the small moving spheres. The motions of the field lines are in the direction of the local Poynting flux vector.

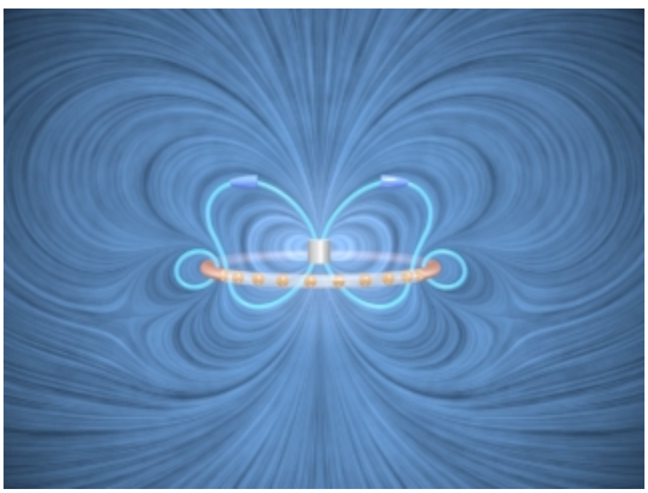

Figure 1. The falling magnet with a zero resistance ring

Assessing the outcomes

Assessment of undergraduate students' achievements is changing, largely because today’s students face a world that will demand new knowledge and abilities, and the need to become life-long learners. Current and future assessment should be based on the constructivist paradigm. In such environment, the student becomes involved not just in the learning but in assessing himself or herself while being responsible for the learning outcomes. Differences between “assessment of learning” and “assessment for learning” are described in the literature (Assessment Reform

Group, 1999; Dori, 2003; Mitchell, 1992). The former relates to assessment for grading and reporting, while the purpose of the latter is to enable students, through effective feedback.

Assessment of the NCSU courses

The NCSU assessment plan was based on the objectives outlined in Table 1. We assessed conceptual understanding by taking advantage of some of the nationally standardized tests that have been developed for the topics of introductory physics courses. These tests were given over many semesters, in pre/posttest modes. Results were uniformly positive. We were especially encouraged by the fact that students in the top tier of the class showed the highest normalized gains, implying they benefited greatly by teaching their peers. We also randomly sampled problems from tests developed by teachers of traditional sections of the courses. In 7 out of 10 cases the experimental students significantly outperformed their cohorts. We also found class attendance to improve from roughly 70% to over 90% when the same teacher switched from traditional to interactive instruction, even though the attendance policy remained the same (attendance was voluntary and would not directly affect grades). By comparing the success rates of more than 16,000 students over a five year time span, we found that students in the experimental sections failed less than half as often. For minorities and women the failure rates were one fourth to one fifth those seen in the traditional classes with similar students. We believe this is due to the social support network that is an outcome of the careful design of the learning environment and activities. Finally, we found that at-risk students from the experimental sections failed a later Engineering Statics course less than half as often as equivalent, but traditionally taught students.

Assessment of the Electromagnetism Course at MIT

To assess the effect of the visualizations and the pedagogical methods implemented in the TEAL project, we examined the scores in conceptual pre- and posttests for the experimental (TEAL students) and the control (traditional lecture and recitation setting) groups. Both the pre- and posttests consisted of 20 multiple-choice conceptual questions from standardized tests (Maloney et al., 2001; Mazur, 1997) augmented by questions of our own devising (Dori & Belcher, 2005A). Based on their pretest scores, students in both research groups were divided into three academic levels: high, intermediate, and low.

The difference in the net gain between the experimental and control groups was significant ($p<0.0001$) for each academic level separately as well as for the entire population. These results suggest that the learning gains in TEAL are significantly greater than those obtained by the traditional lecture and recitation setting. The results are consistent with several studies of introductory physics education over the last two decades (Beichner et al., in press; Hake, 2002). It is also in line with the much lower failure rates for the TEAL course of Spring 2003 (a few percent) compared to traditional failure rates in recent years (from 7% to 13%).

In order to investigate Spring 2003 students' perceptions, we asked them to list the most important elements which contributed to their understanding of the subject matter taught in the TEAL project and explain their selection. We divided their responses into four categories: Oral explanations in class, technology, written problems, and the textbook (Dori et al., 2003). The technology category included desktop experiments performed in groups, 2D and 3D visualizations, individual Web-based home assignments turned in electronically, and individual real-time class responses to conceptual questions using a personal response system (PRS) accompanied by peer discussion. Written problems included both individual problem sets given as home assignments and analytic problems solved in class workshops.

The Spring 2003 questionnaire was completed by 308 students. The results showed that about 40% favored the problem solving method, about 22% selected the technology, 22% selected the textbook, and 16% favored the professor's oral explanations. Typical explanations students gave to their selection of technology-based teaching methods included elements of visualization, desktop experiments, PRS-based conceptual questions, and Web-based assignments. Still, the teacher turned out to be indispensable for both the oral explanations and the problem solving workshops.

Student surveys were administered also during Spring 2004. The goal of this study was to locate patterns that may reveal how TEAL can be further improved from the student learning standpoint. Questionnaires were administered by the TEAL staff at the end of the term and completed by 74.4% of 508 students. After criteria for categorizing answers were developed based on the type of question asked and the responses generated, the survey answers were categorized and frequency percentages of answers were calculated. Figure 2 presents students' responses to the question "*Would you recommend the TEAL Electromagnetism course to a fellow student?*"

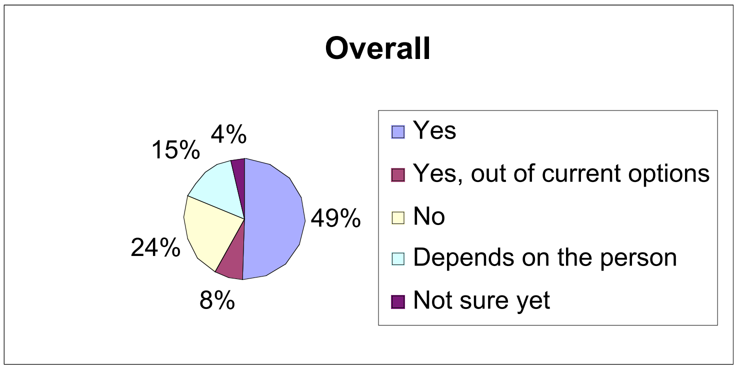

Figure 2. Spring 2004 survey results – Students' responses to the question "*Would you recommend the TEAL Electromagnetism course to a fellow student?*"

About half of the students responded that they would recommend TEAL to fellow students, while a quarter said they would not recommend TEAL. In response to the question "*What are the pros and cons of working in groups in the classroom?*" one student wrote: "The pros are that you get to learn from and teach your fellow classmates which help reinforce the information. If you are working with someone who is ahead of you, it's difficult to learn because you are trying to catch up but you are always pulling that person back. I found that it was a problem at the beginning of the semester when I was the one learning while the other people in my group were flying through all the questions. I felt like I was holding the group back. As the semester rolled on, I was able to catch up but it was difficult the first couple weeks." This response portrays the complexity of students' attitudes toward innovative elements in the TEAL environment (teamwork in this case).

Summarizing the results we found out that there is a large variation in the responses between the various classes. One cause that correlates well with the data is how responses varied with the professor teaching the class. Certain professors consistently had better results than others, especially over those who had never taught in the TEAL learning environments before. Another pattern that evolved was that students felt that TEAL might not be an effective environment for everyone due to differences in personal learning habits.

Conclusions

Science educators are facing increasing demands as they are asked to teach more content more effectively and to engage their students in scientific practices (Edelson, 2001). The National Science Education Standards (National Research Council [NRC], 1996) expressed strong disapproval of the traditional emphasis on memorization and recitation. They stressed the need to foster conceptual understanding and give students the firsthand experience of questioning, gathering evidence, and analyzing that resembles authentic scientific processes. Science teachers' conceptions of science and the way they teach it is a result of the way they were taught in their schools (Hewson & Hewson, 1989). The methods by which science instructors were taught are often inconsistent with contemporary educational approaches. This state of affairs calls for a comprehensive conceptual change in the way science is taught in higher education. Such a change on the part of science faculty requires the development and implementation of new curricula and the adaptation of new teaching and assessment methods that foster conceptual understanding. The NCSU and MIT TEAL projects foster individual and group thinking, supported by hands-on activities, visualizations, and small and large group discussions for knowledge building. Aiming at enhancing conceptual understanding of mechanics and electromagnetism phenomena, these two projects are designed to actively engage students in the learning process, using technology-enabled methods as appropriate. One should bear in mind that in this type of basic physics courses, students traditionally have been accustomed to classes that are made up of passive lectures that closely follow a particular textbook. Direct hands-on exposure to the phenomena under study, visualization of electromagnetic phenomena, and active learning in a collaborative setting were combined to achieve the desired effect on the students' learning outcomes.

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For further information, visit the SCALE-UP website, http://scaleup.ncsu.edu and the MIT website, http://ocw.mit.edu.

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