Technology for active learning

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Problems related to passive learning in large undergraduate physics classes were first identified and researched over a decade ago[1] and are still under investigation[2,3]. Students experience difficulties in learning physics because they must fully understand concepts and principles of the physical world that are sometimes impossible to see (as in electromagnetism phenomena) and often difficult to comprehend. On top of these difficulties, there are the requirements to master quantitative and formulaic representations of scientific phenomena in order to conceptualize and use them in work[4].

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Traditional science courses, even nowadays, present science as a collection of facts, while scientific methodology is presented as homogeneous and based on empirical research. This leads to a static and context-independent view of discovery outcomes. Students are required to memorize facts without questioning either their development or relationship to other scientific or nonscientific knowledge[5].

These problems, which result in high attrition and failure rates among students, have been found in both high school and undergraduate physics courses. Some researchers cite the lack of a common language between mathematicians and physicists as the root of learning difficulties experienced by physics students[6]. Other studies place the blame on traditional teaching methods, which reward memorization over conceptual thinking[7] or just simply do not address adequately the needs of individual classes[8].

Cognitive psychologists and educators have pointed to a strong relation between visual abilities and learning science[9]. Problem solving in physics often requires visualizing abstract physical concepts or manipulating diagrams and graphs, demanding high visual and cognitive capabilities. Hestenes emphasized the necessity of developing teaching models that encourage conceptual understanding in physics classrooms[10].

Teaching models are playing an increasing role in the science curriculum[11]. Science educators and instructors agree that students need to understand the models of scientific phenomena with which they are presented[12] and to be able to construct their own[13]. If students are to fully understand a model's nature and implications, it should cover a broad

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range of modes[12,14], including concrete, verbal, symbolic, mathematical, and visual.

This review reports on the Technology-Enabled Active Learning (TEAL) Project at Massachusetts Institute of Technology (MIT)[15]. In the TEAL project, we use mathematical, concrete, and visual modes of representations. Our media-rich visualizations of electromagnetic phenomena are based on Java simulations, three-dimensional illustrations and animations, and ShockWave visualizations[16].

TEAL project: motivation and setting

The motivation for moving to a different mode of teaching introductory physics courses was threefold. First, the traditional lecture and recitation format for teaching the mechanics and electromagnetism courses at MIT had a 40-50% attendance rate, even with good lecturers, and a 10% or higher failure rate. Second, a range of educational innovations in teaching freshman physics had demonstrated that any pedagogy using 'interactive-engagement' methods results in higher learning gains than the traditional lecture format[2,17,18]. Finally, unlike many educational institutions in the US and around the world, the mainline introductory physics courses at MIT had not included a laboratory component for over three decades. This was something we wanted to re-introduce.

The objective of the TEAL project is to transform the way physics is taught to large physics classes at MIT in order to decrease failure rates and increase students' conceptual understanding. Visualization technology can support meaningful learning by enabling the presentation of spatial and dynamic images, which portray relationships between complex concepts. The first course selected to be transformed into the TEAL format was Electricity and Magnetism (E&M). The reason for this choice was that the topics discussed in the course are of abstract nature and visualization can potentially alleviate students' difficulties in understanding.

The TEAL project is centered on an 'active learning' approach, aimed at helping students visualize, develop better intuition about, and conceptual models of electromagnetic phenomena. Taught in a specially designed classroom with extensive use of networked laptops, this collaborative, hands-on approach merges lectures, recitations, and desktop laboratory experience in a media-rich environment. In the TEAL classroom, nine students sit together at round tables (Fig. 1), with a total of thirteen tables.

Five hours of class per week is broken into two, two-hour sessions and a one-hour problem-solving session led by graduate student teaching assistants. The students are exposed to a mixture of presentations, desktop experiments, web-based assignments, and collaborative exercises. The desktop experiments and computer-aided analysis of experimental data provide the students with direct experience of various electromagnetic phenomena.

It should be noted that the Fall 2001 E&M course was taught by two instructors, one of whom (the second author) initiated and led the TEAL project, while the other was part of the development team. In Spring 2003, there were six new instructors, none of whom had previously been involved in TEAL and some of whom were not comfortable with using the media-rich environment.

Fig. 1 Undergraduate physics students in the d'Arbeloff Studio Classroom.

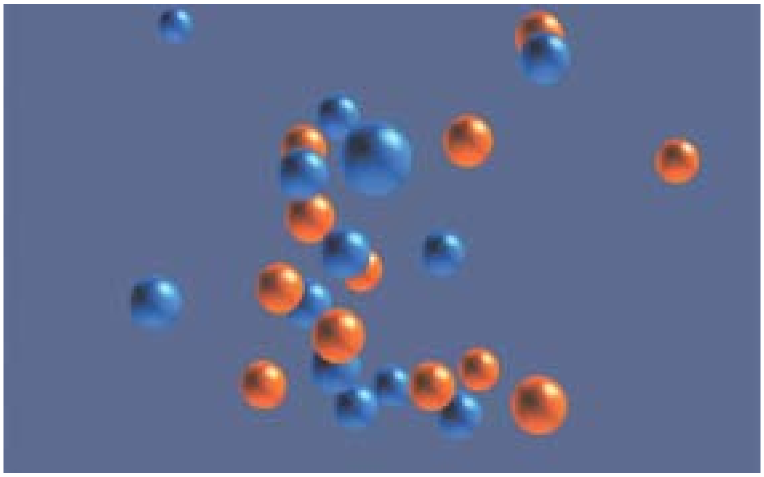

Fig. 2 The 'Molecules 3D' visualization.

Visualizations

Patterned in some ways after the Studio Physics project of Rensselaer Polytechnic Institute[19] and the Scale-Up project of North Carolina State University[20], TEAL extends these efforts by incorporating advanced two- and three-dimensional visualizations that employ Java applets. The 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. For a selection of the visualizations, see[21,22]. Such animations allow students to intuitively relate the forces transmitted by electromagnetic fields to more tangible forces. The following three examples show visualizations developed especially for and used in the TEAL E&M course.

In the topic of electrostatics, the '*Molecules 3D'* visualization[23] simulates the interaction of charged particles in three-dimensional space (Fig. 2). The particles interact via the classical Coulomb force, as well as the repulsive quantum-mechanical Pauli force, which acts at close distances (accounting for the 'collisions' between them).

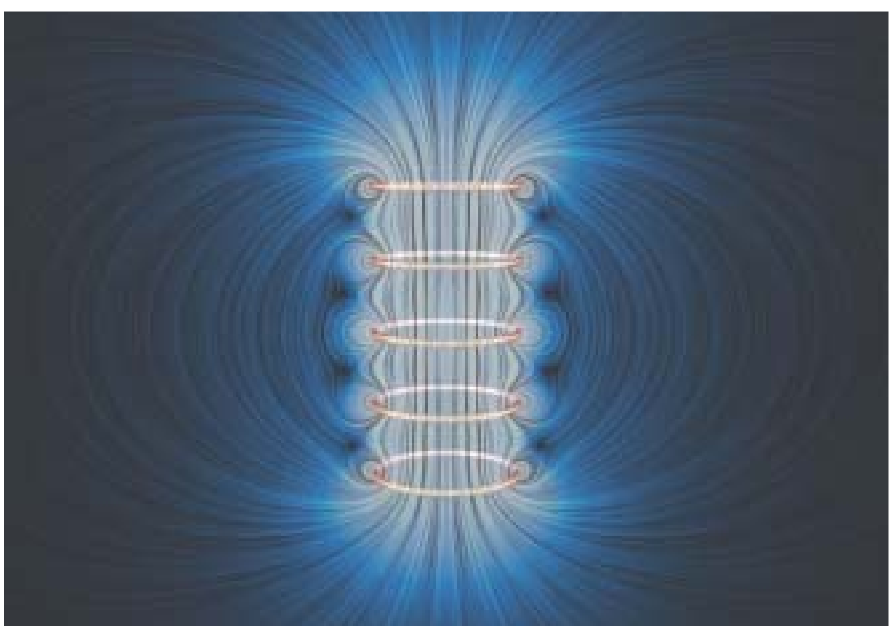

Fig. 3 The 'Creating a Magnetic Field' visualization.

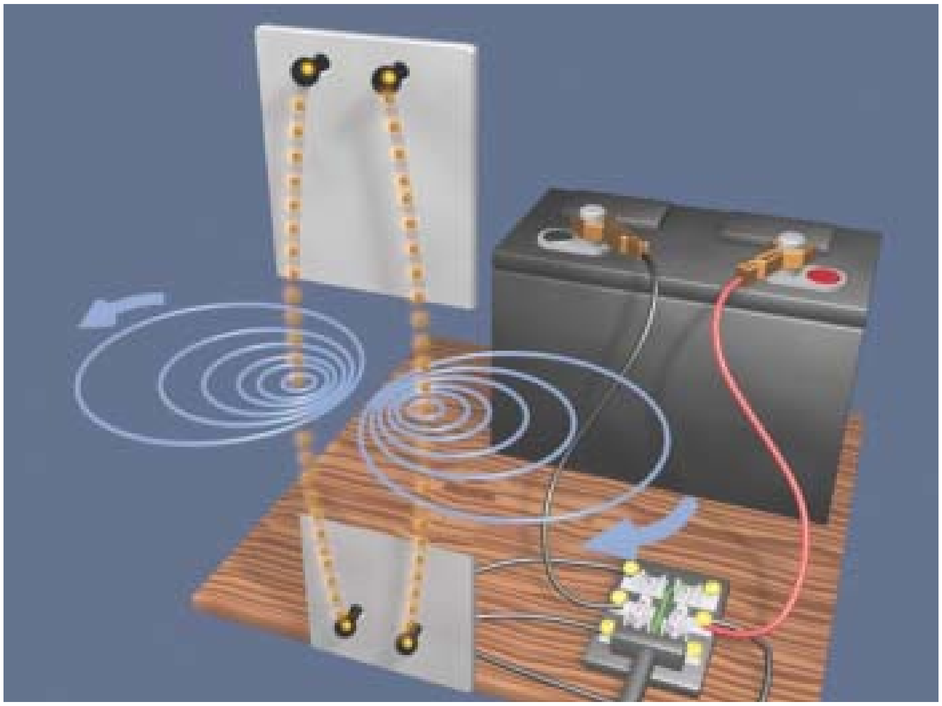

Fig. 4 The 'Two Wires in Series' visualization.

The motion of the particles is also damped by a term proportional to their velocity, allowing them to 'settle down' into stable (or metastable) states.

The '*Creating a Magnetic Field*' visualization[24] illustrates Faraday's Law (Fig. 3). It assumes that we have five rings carrying a number of free positive static charges. Since there is no current, there is no magnetic field. Suppose a set of external agents come along (one for each charge) and spin up the charges counterclockwise, as seen from above, at the same time and rate, in a pre-arranged manner. Once the charges on the rings start to accelerate, there is a magnetic field in the space between the rings, mostly parallel to their common axis, which is stronger inside the rings than outside. This is the solenoid configuration. As the magnetic flux through the rings grows, Faraday's Law tells us that there is an electric field induced by the time-changing magnetic field, which is circulating clockwise as seen from above. So the force on the charges caused by this electric field is opposite to the direction in which the external agents are trying to spin the rings up (counterclockwise). The agents then have to do additional work to spin up the charges. This is the source of the energy in the magnetic field between the rings.

In magnetostatics, the '*Two Wires in Series*' visualization[25] shows the magnetic field configuration around two wires carrying current in opposite directions (Fig. 4). The Maxwell stresses associated with the magnetic fields cause the wires to feel a mutual repulsion, and they spread apart as a result.

Study setting and method

This study focuses on students' perceptions of the visual representations, along with other teaching methods, as tools to comprehend abstract concepts.

We present and analyze the educational impact of the TEAL approach using questionnaire results obtained after the Fall 2001 and Spring 2003 courses. The assessment of students' learning outcomes in the TEAL project, which are reported elsewhere[26], strongly suggests that the learning gains are significantly greater than those obtained in the traditional lecture and recitation setting. The results are consistent with other studies of introductory physics education over the last two decades[27]. 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%).

The students were asked to list the most important elements that contributed to their understanding of the taught subject matter and explain their selection. We divided their responses into four categories: oral explanations in class, technology, written problems, and textbooks[28]. The technology category included: desktop experiments performed in groups; two- and three-dimensional visualizations; individual, web-based home assignments submitted 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 analytical problems solved in class workshops.

The experiment started in Fall 2001, and continued throughout Spring 2003, involving about 350 students. By Fall 2001, the physical infrastructure for teaching the course in the d'Arbeloff Studio Classroom was in place. The experimental group of Fall 2001 included about two-thirds upper classmen, who had failed either the mechanics course or the E&M course. One third was comprised of freshmen that had either studied physics in high school at an advanced level or taken the examination for the advanced placement mechanics course. Therefore, most of the Fall 2001 students were to some extent familiar with basic E&M concepts. We expanded the TEAL Project such that full implementation of the course took place in Spring 2003, encompassing about 600 students and six new instructors. The students consisted of 90% freshmen and 10% upper classmen, so most of them had never been exposed to the E&M learning material before.

Findings

The Fall 2001 and Spring 2003 questionnaires were completed by 174 and 308 students, respectively. The results are presented in Fig. 5 and Table 1.

Fig. 5 shows that three of the four categories are equally important. The role of problem solving is highest in both years. A frequent student complaint in the Spring 2003 questionnaire was that "the blind can't lead the blind" in group work. Students complained that they felt they did most of their learning outside class.

Typical reasons given by students to explain their selection of technology-based teaching methods included elements of visualization, desktop experiments, PRS-based conceptual questions, and web-based assignments (Table 1). However, the teacher remains indispensable for both the oral explanations and the problem-solving workshops.

Discussion

Science educators are facing increasing demands as they are asked to teach more content, more effectively, and engage

Table 1 *Sample explanations given by 2003 students to explain their selection of the various teaching methods.*

Teaching method		Student's explanation
Oral explanations in class		Having teachers at our disposal when we have questions with specific problems is possibly the best aspect of TEAL.
Technology	Desktop experiments	The experiments were interesting, but often not easy to learn from.
	Two- and three-dimensional visualizations	The visuals and simulations were great for conceptualizing and visualizing how electric and magnetic fields interact with charged particles/wires/etc., and what affects, creates, and changes them. The three-dimensional visualizations are the one thing that I can't get from a book or learning on my own.
	Web-based home assignments	I think the readings for the web assignments were really important. They forced me to actually do the readings before class.
	Conceptual questions using PRS	PRS was the best part of class because it took general concepts and shrank them down into concise, multiple-choice questions that both reviewed old stuff and taught new things. We get to test our knowledge without fear of failure.
Written problems	Home assignments	The problem sets offered the main opportunity to connect material presented in class and figure out how it related to actual material covered in exams.
	Class workshops	The workshops help me most because I seem to be learning a great deal from working with other students and discussing questions with them.
Textbooks		I learn the most from the textbook because I can learn at my own pace and go back over concepts that I don't understand as many times as I want.

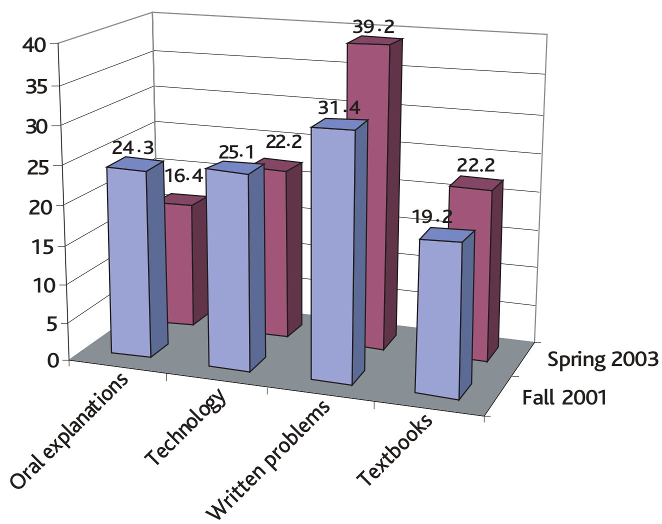

Fig. 5 Students' responses to the teaching method questionnaires.

their students in scientific practices[29]. The National Science Education Standards[30] express strong disapproval of the traditional emphasis on memorizing and reciting facts. They stress the need to foster conceptual understanding and give students firsthand experience of questioning, evidence gathering, and analysis, which resembles the process of authentic science. In the TEAL project, direct hands-on exposure to the electromagnetic phenomena under study, visualization of those phenomena, and active learning in a collaborative setting were combined to achieve the desired effect on the students' learning outcomes.

Our results[26] have shown that problem-solving sessions, two- and three-dimensional visualizations, along with collaborative desktop experiments, web-assignments, and PRS-based conceptual questions, significantly enhance students' understanding of electromagnetism. In Spring 2003, when the teachers were novices in the TEAL approach, students' perceptions were indicative of the potential of this approach on the one hand, and of the need to improve teachers' integration of the educational technology into the E&M course on the other. MT

Acknowledgments

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