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## LEARNING ELECTROMAGNETISM WITH VISUALIZATIONS AND ACTIVE LEARNING

**Abstract.** This chapter describes learning electromagnetism with visualizations and focuses on the value of concrete and visual representations in teaching abstract concepts. We start with a theoretical background consisting of three subsections: visualization in science, simulations and microcomputer-based laboratory, and studies that investigated the effectiveness of simulations and real-time graphing in physics. We then present the TEAL (Technology Enabled Active Learning) project for MIT's introductory electromagnetism course as a case in point. We demonstrate the various types of visualizations and how they are used in the TEAL classroom. A description of a large-scale study at MIT follows. In this study, we investigated the effects of introducing 2D and 3D visualizations into an active learning setting on learning outcomes in both the cognitive and affective domains. We conclude by describing an example of TEAL classroom discourse, which demonstrates the effects and benefits of the TEAL project in general, and the active learning and visualizations in particular.

### INTRODUCTION

The issues related to problematic learning in large passive undergraduate physics classes were first identified and researched over a decade ago (McDermott, 1991). This problem is still under investigation (Hake, 1998; Maloney, O'Kuma, Hieggelke & Van Heuvelen, 2001). Some researchers cite the lack of a common language between mathematicians and physicists as the root of the learning difficulties of students who study physics (Dunn & Barbanel, 2000). Other researchers place the blame on traditional teaching methods that reward memorization over conceptual thinking (Mazur, 1997). Yet others claim that instructors do not adequately address the individual needs of students (Novak, Patterson, Gavin & Christian, 1999). Hestenes (2003) emphasized the necessity of developing teaching models which stress conceptual understanding in physics classrooms. Woolnogh (2000) noted that 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 agree with these later researchers. We also strongly believe that teachers and students need to incorporate visualizations in the teaching and learning of scientific phenomena and processes, especially when dealing with abstract concepts such as electromagnetism (Dori & Belcher, 2004).

In this chapter we argue and demonstrate that visualization technology can support meaningful learning by enabling the presentation of spatial and dynamic images. Such images can portray and illuminate relationships among complex concepts. The Technology-Enabled Active Learning (TEAL) Project at MIT (Belcher, 2001) involves the use of visualization in a collaborative learning environment of a freshman electricity and magnetism (E&M) course. The objective of the TEAL Project was to transform the way physics is taught in large enrollment physics classes at MIT in order to decrease failure rates and increase students' conceptual understanding. The approach is designed to help students visualize, develop better intuition about, and develop better conceptual models of electromagnetic phenomena. Patterned in some ways after the Studio Physics project of RPI (Cummings et al., 1999) and the Scale-Up project of NCSU (Beichner, et al., 2002; Handelsman et al., 2004), TEAL extends these efforts by incorporating advanced 2D and 3D visualizations to enable students to construct 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 appreciate the correspondence between electromagnetic stresses and phenomena that they already understand

Following the theoretical background section, this chapter focuses on the value of concrete and visual representations in teaching abstract concepts. We will use the TEAL project in the E&M course at MIT as a case in point to demonstrate the various types of visualizations and how they are used in the classroom. We conclude by briefly presenting the effects of introducing 2D and 3D visualizations in an active learning setting on undergraduate students' learning outcomes in both the cognitive and affective domains.

## THEORETICAL BACKGROUND

The AAAS report (1989) "Science for all Americans" recommended that reform in science education be founded on "scientific teaching." Scientific teaching approaches the teaching of science with the same rigor as science is approached at its best. However, changes in this direction have neither progressed rapidly, nor have they been driven by research universities as a collective force (Handelsman, Ebert-May, Beichner, Bruns, Chang, DeHaan, Gentile, Lauffer, Strwart, Tilghman, & Wood, 2004). While there is agreement that active participation in lectures and discovery-based laboratories help students develop science-oriented thinking, most introductory courses still rely on "transmission-of-information" lectures and "cook-book" laboratory exercises.

### *Visualization in Science*

Science and technology develop through the exchange of information, much of which is presented as still and moving images, diagrams, illustrations, maps, plots, and models that summarize information, and help others to understand scientific data and phenomena (Mathewson, 1999). To fully understand the nature and implications of scientific phenomena and their models, students should be exposed to a broad array of types of models, such as concrete, verbal, symbolic, mathematical, and visual models (Boulter & Gilbert, 2000; Gilbert & Boulter, 2000; Treagust, 1996).

Teaching science requires that the learning materials be presented not only through words—in spoken or printed text—but also through pictures—still and moving pictures, visual simulations, 2D and 3D visualizations, graphs, and illustrations. Pictures are superior to words for remembering concrete concepts (Rieber, 2002). The dual coding theory (Paivio, 1990; Sadoski & Paivio, 2001) suggests a model of human cognition divided into two dominant processing systems—verbal and nonverbal. The verbal system specializes in "language-like" processing, while the nonverbal system includes vision and emotions.

The cognitive theory presented by Mayer (2002) offers three theory-based assumptions about how people learn from words and pictures. The first assumption is the *dual channel* assumption, which is essentially the same as Paivio's dual coding theory (1990). Mayer suggested that knowledge is represented and manipulated through both through the visual-pictorial channel and the auditory-verbal channel. Mayer's second assumption, called *limited capacity* emphasizes that the channels can become overloaded when a large volume of spoken words or pictures are presented. The third assumption, *active processing*, is that meaningful learning occurs when students engage in active learning. They select relevant words and pictures, organize them into pictorial and verbal models, and integrate them with prior knowledge. These active learning processes are most likely to occur when corresponding verbal and pictorial representations are in working memory at the same time.

Visualization technologies were initially pioneered for the representation of complex scientific data and models. Eventually, these visualizations have found their way into science education, focusing on enhancing students' scientific inquiry while they are involved in data analysis and modeling (Jacobson, 2004). Scientists and science educators have therefore argued that visualization of phenomena and laboratory experiences are important components for understanding scientific concepts (Cadmus, 1990; Escalada, Grabhorn, & Zollman, 1996). Demonstrations, simulations, models, real-time graphs, video, and visualizations can contribute to students' understanding of scientific concepts by providing mental images to go with abstract concepts. They enable the capture and perseveration of the essence of such phenomena more effectively than verbal or textual descriptions. The National Science Education Standards describes the learning of science as an active process (National Research Council, 1996) that implies a physical ("hands-on") and mental ("minds-on") activity.

According to Mathewson (1999), visual-spatial thinking includes both vision and imagery. Vision refers to the process of identifying, locating and thinking about objects in the world. Imagery is the more abstract process, carried out in the absence of a visual stimulus, in which we engage in formation, inspection, and transformation of images in the "mind's eye". Suwa and Tversky (2002) claimed that representations such as diagrams, sketches, charts and graphs serve not only as memory aids but also as aides for inference, problem solving, and to facilitate thinking about entities or elements and their spatial array. Thinking about functional aspects of the situation from these representations requires associations and inferences from the visio-spatial display to more

abstract concepts. Their study showed that experts are more adept than novices at perceiving functional thoughts from representations.

Discussing dynamic mental models in learning science, Frederiksen, White, and Gutwill (1999) characterized two levels of models. Lower-level models focus on concrete phenomena, such as the electrostatic interaction of charged particles, and employ causal reasoning about object interactions. Higher-level models focus on more abstract representations of variables and the relationships among them. Developing conceptual links from lower- to higher-level models helps students explain interactions and behaviors and improves their performance in solving problems.

Focusing on the role of problem representation in physics, Larkin (1983) attributed many differences in the problem-solving performance of experts and novices to the use of different representations. A naïve representation contains direct, familiar, visible entities, found directly in the problem. More advanced physical representations include qualitative, time-independent, and redundant inference rules and intangible artifacts (forces, moments, fields, etc.) that invoke fundamental principles of physics. When solving physics problems, novices base their representations and approaches on the problem's literal features, while experts apply physical principles and integrate the representation with prior knowledge (Chi, Feltovich & Glaser, 1981). Experts also spend time constructing abstract representations for such variables as force and energy, to reduce the amount of information that must be attended to at any one time (Larkin, McDermon, Simon, & Simon, 1980).

### *Simulations and Microcomputer-Based Laboratory in Physics*

During the past decade, a number of physics curricula for undergraduate students have been developed that utilize outcomes from educational research. These include *Physics by Inquiry* and *Tutorials in Introductory Physics* (McDermott, 1991; McDermott & Shaffer, 2002), *Tools for Scientific Thinking* (Thornton & Sokoloff, 1990), *Matter & Interaction* (Chabay & Sherwood, 2002), *Peer Instruction*, (Mazur, 1997) and the calculus-based physics without lectures course *Workshop Physics* (Laws, 1991). Projects that incorporated Information & Communication Technologies (ICT) include *Real-Time Physics* (Sokoloff, Thornton & Laws, 1999), *Studio Physics* at Rensselaer Polytechnic Institute (Cummings, Marx, Thornton & Kuhl, 1999), and the SCALE-UP project at North Carolina State University (Beichner, Bernold, Burnston, Dali, Gastineau, Gjertsen & Risley, 1999), as well as the TEAL Project at MIT (Dori, Belcher, Bessette, Danziger, McKinney & Hult, 2003). Common characteristics of these innovative courses included activity-based pedagogies, collaborative learning, the integration of curricula, context-rich problems, and the use of technology.

ICTs, which are in daily use in physics research, are slowly finding their way into physics teaching. Although many textbooks and software devoted to computational physics exist, many physics courses in college and universities are still taught in the traditional manner. In the best cases, special courses on simulation and computational physics are taught, but the introductory courses usually make little use of the possibilities opened up by ICT.

In what follows, we present several simulations and applications of Microcomputer-Based Laboratory (MBL) in physics. In the following section, we describe studies on the effectiveness of simulations and MBL in physics education.

Martinez-Jimenez and Casado (2004) developed a computer-aided education package, *Electros*, especially designed for introductory physics courses. The software evolved from the experience with physics and engineering undergraduate students. *Electros*, which focuses on electrostatic fields and potentials produced in the presence of dielectrics, has, in addition to the simulation, a tutorial, an initial test, and a final test.

Cox, Belloni, Dancy and Christian (2003) developed interactive Physlet-based curricular material to help students learn concepts of thermodynamics, with a particular focus on kinetic theory models. The simulations help students to visualize ideal gas particle dynamics and engine cycles, make concrete connections between mechanics and thermodynamics, and to develop a conceptual framework for problem solving. Students can determine the efficiency of a simplified version of real-world combustion engine and this helps them connect the abstract *PV* diagrams of physics and chemistry to a real-life car engine.

Escalada, Rebello and Zollman (2004) developed another package, *Visual Quantum Mechanics—The Next Generation*, that includes simulation, computerized tools, and instructional strategies for undergraduate physics majors. This package focuses on enabling students to make observations, develop mental models consistent with quantum principles, and apply these models to related situations. For example, while students carried out visualization activities, they developed a model of waves of matter, explained discrete energy states, and examined applications to the electron microscope.

Chabay (2002) supplemented an electromagnetism textbook (Chabay & Sherwood, 2002) with short 3-D QuickTime movies of electric and magnetic fields in space. The movies, which depict spatial configurations of electric and magnetic fields that are frequently discussed in introductory physics courses, are designed to address beginning students' difficulties in visualizing fields throughout space. Two-dimensional diagrams or static images are not sufficient for three-dimensional reasoning about fields. This is so because magnetic field and force vectors

are computed using vector cross products, and thus these fields and vectors inherently involve three dimensions. A common misconception, which is exacerbated with time-varying fields, involves thinking in general terms of "the field" rather than precisely of the field vector at a particular location in space and time.

The MBL, also called *desktop experiments*, is yet another means to foster students' understanding of physical phenomena through visualization. Designed to collect data via various probes such as motion, light, temperature, force, pressure, sound, or current, typical MBL applications store or feed the data into a computer. This data can then be analyzed and displayed using many different representations, enabling the student to gather the data in real-time and then graph it either at a later time or simultaneously (Kown, 2002; Lapp, 1999).

The Studio Physics at Rensselaer Polytechnic Institute (Cummings, Marx, Thornton & Kuhl, 1999) combined MBL with the studio approach, where students are actively involved in class experiments and small group discussions. At RPI, the Introductory Studio Physics was a calculus-based, two-semester sequence equivalent to the standard physics for engineers and scientists, in which large classes were broken into small sections.

### *Studies on Simulations, MBL, and Real-time Graphing*

Having reviewed several examples of physics simulation, we now turn to a more theoretical and empirical-based discussion on this subject. Steinberg (2000) investigated the impact of using a computer simulation in a classroom studying the behavior of objects moving under the influence of air resistance by comparing two classes which both had interactive learning environment. One class used the simulation, while the other used only paper and pencil activities. Although there were differences in how students approached learning, students' performance on a common exam question on air resistance was not significantly different. The author claimed that a computer simulation that quickly and transparently delivers exact answers can result in students learning science passively, and there is a danger that students will see no need to take responsibility for their own understanding, verification, or inquiry. On the other hand, many students used the air resistance simulation actively and productively, considering more complex problems than were possible without the computer.

Several studies compared the effects of simulation-based-learning to various types of expository teaching. Some of these studies which dealt with physics focused on Newtonian mechanics (Rieber, Boyce, & Assad, 1990; Rieber, Noah & Nolan, 1998; Rieber & Parmley, 1995; White, 1993) and on electrical circuits (Carlsen, & Andre, 1992). These studies showed that learning with computer simulation is as effective as expository instruction; however, they also suggest that effects of simulation-based-learning are stronger when the simulation is embedded in an environment that intends to support specific aspects of discovery learning.

Learners using simulations can be given assignments or be exposed to model progression, i.e., viewing the simulation gradually, avoiding exposure to its full complexity from the beginning. De Jong, Martin, Zamarro, Esquembre, Swaak, and van Joolingen (1999) evaluated a simulation of collisions in a discovery environment. They concentrated on the effect of providing support for the planning process by means of presenting freshmen with assignments and model progression. One group of students worked with assignments-enhanced simulation. Students in the second group were free to select their assignments while using a model progression in addition to the assignments. The control group used an unsupported simulation. Research results contributed to the understanding of how to support learners in their discovery learning process. Assignments helped learners gain intuitive knowledge, but the role of model progression was unclear.

Several studies on the effect of MBL on students' learning outcomes focused around real-time graphing. The immediacy of graph production can help students develop the cognitive linkage between the occurrence of an event and the graphic representation, while focusing more on what was happening in an activity. However, misconceptions in using and interpreting graphs may include referring to the graph as a picture and confusing slope with height and shape with path of motion (Dunham & Osborne, 1991; Mokros & Tinker, 1987; McDermott, Rosenquist & van Zee, 1987; Goldberg & Anderson, 1989). Brasell (1987) showed that the standard MBL approach was significantly better than delayed MBL or pencil-and-paper approaches due to the immediacy of the graph production experienced in the standard MBL groups. Beichner (1989) suggested that the simultaneity of the physical event and its graphical representation is not the only feature that makes MBL effective; the ability of the student to control the environment may also play a vital role in understanding of physical events.

In high school physical science, Stein (1987) investigated features of an MBL implementation and observed a high degree of student autonomy in troubleshooting and sharing of data when students formed consulting groups for cooperative remediation of problems. In chemistry, Nakhleh and Krajcik (1994) found that high school students constructed more concepts using MBL. In addition, careful analysis of the task, directed teaching, and class discussion were needed to prevent the formation of misconceptions. In physics, Trumper and Gelbman (2000) described an MBL experiment designed for high-school students that analyses very accurately Faraday's law of electromagnetic induction. The authors stated that the MBL tools provided a clear and concrete illustration of this law and that the learning provided a link between a concrete experience and the symbolic representation.

The objective of the research conducted by Cummings et al. at Rensselaer Polytechnic Institute (1999) was to determine if incorporation of research-based activities into Studio Physics would have a significant effect on

conceptual learning gains. The researchers used the Force Concept Inventory and the Force and Motion Conceptual Evaluation to verify the effectiveness of interactive lecture, demonstrations, and cooperative group problem solving. The study implied that the standard Studio format used for introductory physics instruction at Rensselaer is no more successful at teaching fundamental concepts of Newtonian physics than traditional instruction. This result is in line with an earlier study (Redish, Saul, & Steinberg, 1997).

The SCALE UP project (Beichner, Bernold, Burnsiton, Dali, Gastineau, Gjertsen & Risley, 1999) was accompanied by research aimed at investigating the effect of the approach on students' achievements and attitudes. During class activities, students had to make predictions, develop models of physical phenomena, collect and analyze data from MBL-type probes, and work on design projects. They were responsible for reading material from the textbook and asking questions. The assessment tools included the Force Concept Inventory, the Test of Understanding Graphs in Kinematics, problem-solving tasks and a final examination. The type of instruction used in the experimental courses, a highly collaborative, technology-rich, activity-based learning environment, had a substantial positive effect on the students' conceptual understanding and confidence levels. This project demonstrated that when implemented properly, the Studio Physics approach is viable and effective. This result encouraged us to propose the TEAL Project at MIT.

## THE TEAL PROJECT

In this chapter, we describe the Technology-Enabled Active Learning (TEAL) Project at MIT (Belcher, 2001) as an illustration of the use of visualizations in teaching science. Founded on theoretical underpinnings of cognition (Paivio, 1991; Mayer, 2002), the TEAL project uses both passive and interactive visualizations of phenomena that cannot ordinarily be seen, integrated with textual explanations that immerse the students in an active learning environment. The TEAL visualizations of electromagnetism phenomena (Belcher & Bessette, 2001; Belcher & Olbert, 2003; Dori et al., 2003) are created using such technologies as Java 3D simulation of desktop experiments, ShockWave visualizations, and passive movies made using 3ds max, a commercial 3D modeling and animation software program.

### *Motivation and Setting*

The TEAL Project represents an innovative style of teaching introductory physics at MIT. An important objective of the TEAL project was to transform the way physics is taught in large enrollment physics classes at MIT in order to decrease failure rates and to increase students' conceptual understanding.

The motivation for the transition from the traditional lecture and recitation mode to this different mode was threefold. First, the traditional format for teaching the mechanics and electromagnetism courses at MIT have had a 40-50% attendance rate, even with spectacularly good lecturers, and a 10% or higher failure rate. Second, a range of educational innovations in teaching freshman physics over the last two decades have demonstrated that any pedagogy using "interactive-engagement" methods results in higher learning gains than the traditional lecture format (e.g., Halloun and Hestenes 1985, Hake 1998, Crouch and Mazur 2001). Third, unlike many educational institutions in the United States and around the world, the mainline introductory physics courses at MIT have not had a laboratory component for over three decades, and TEAL was designed to re-introduce a laboratory component to the mainline courses. Visualization technologies can support meaningful conceptual learning by enabling the presentation of spatial and dynamic images that portray relationships among complex concepts. This is particularly true in electromagnetism, in that the topics discussed in this subject are highly abstract in nature and visualization can potentially alleviate difficulties in students' understanding of electromagnetic field concepts.

The TEAL project is centered on an "active learning" approach, aimed at helping students visualize, develop better intuition about, and better conceptual models of, electromagnetic phenomena (Dori & Belcher, 2004). Taught in a specially designed classroom with extensive use of networked laptops, this collaborative, hands-on approach merges lecture, recitations, and desktop laboratory experience in a media-rich environment. In the TEAL classroom, nine students sit together at round tables (see Figure 1), with a total of thirteen tables.



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

In five hours of class per week (two two-hour sessions and one one-hour problem-solving session led by graduate student TAs), the students are exposed to a mixture of presentations, visualizations, desktop experiments, problem solving and collaborative exercises. The desktop experiments and computer-aided analysis of experimental data provide the students with direct experience of various electromagnetic phenomena.

#### ELECTROMAGNETISM VISUALIZATIONS IN TEAL

The visualizations of electromagnetic phenomena embedded in the TEAL project allow students to gain insight into the nature of electromagnetic fields in several ways.

First, the students can appreciate the manner in which fields transmit forces between material objects by watching how the motions of those objects evolve in time in response to the forces. Such visualizations allow students to intuitively relate the forces transmitted by electromagnetic fields to more tangible forces that are directly part of their daily experiences. Examples of such experiences include the forces exerted by strings and rubber bands. Moreover the TEAL visualizations are in many cases *virtual* models of *real* desktop experiments that the students interact with in the class. This makes the physical phenomena associated with fields more concrete by enhancing the feel for reality through adding such artifacts as magnetic field lines embedded in a virtual version of a real experimental setting.

Second the TEAL visualizations employ the display of time-varying graphs of physical parameters such as electric current, which are obtained in real time by sensors hooked to laptops. The data are captured and recorded while students perform the experiments, and are amenable to graphic display modes and further analysis.

The TEAL visualizations are both passive and interactive. The passive visualizations are in the form of mpeg movies generated with 3ds max. They have the advantage of being highly detailed and representing the interaction of material objects with fields at high resolution. These visualizations achieve graphical quality that cannot be reached with a real-time simulation.

The interactive visualizations display lower resolutions than the passive mpeg movies and are of lower graphical quality. However, unlike a passive visualization, interactive visualizations enable the viewer to manipulate elements on the screen and/or control variables so he or she can get a more direct feeling of the phenomenon being demonstrated and experience it with higher involvement than in a passive visualization. Interactive visualizations in the TEAL project further split into simulations and graphs resulting from hands-on desktop experiments.

Following are several black and white examples of visualizations developed especially for and used in the TEAL Electricity and Magnetism (E&M) course. For a wider selection of color and animated passive and active visualizations see <http://web.mit.edu/8.02t/www/802TEAL3D> or the accompanying CD. Each visualization example is supplemented with an explanation of the underlying physical principles and equations that explain the phenomenon being visualized.

As an example of an interactive visualization in electrostatics, Figure 2 shows an “electrostatic video game” Java 3D applet that helps the student understand how electrostatic fields mediate the attraction of unlike charges and the repulsion of like charges. The student maneuvers a ball around an enclosure by changing the charge on the ball from positive to negative and back again, using the slider shown in the figure. As the charge on the ball is changed, the ball can be moved around the enclosure because of its repulsion or attraction from two stationary and fixed positive charges whose charge does not change. The object of the game is to maneuver the ball through the “gate” at the lower right of the enclosure in the shortest possible time. The educational purpose of this game is to illustrate in a visceral way the electrostatic field “tension” or “pressure” that leads either to attraction or

repulsion between particles of unlike charge or like charge, respectively. The student maneuvering the ball by changing its charge sees the constant interplay of tension versus pressure as he or she moves the charge around the enclosure.

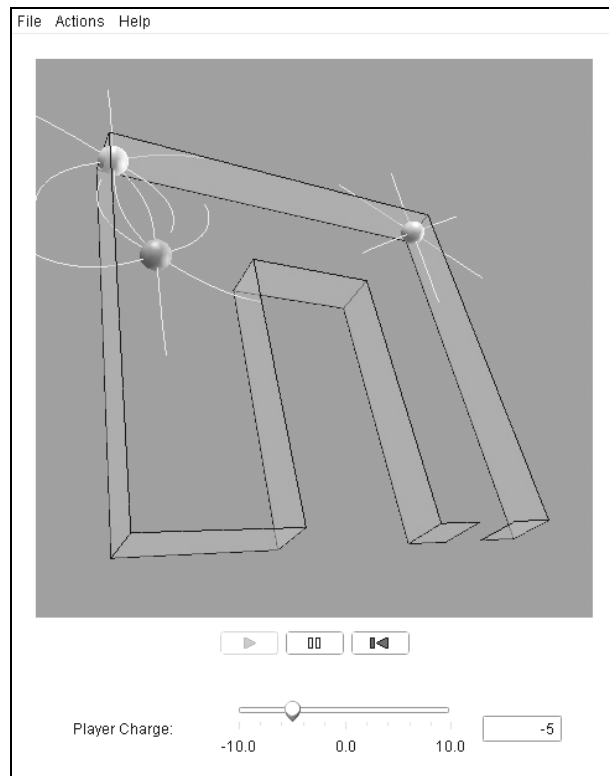


Figure 2. An interactive electrostatic video game illustrating how the interaction of charges is mediated by their electric fields

Turning to the topic of magnetostatics, we first present the "Floating Coil" passive visualization. This visualization simulates the magnetic fields generated by a permanent magnet and a current-carrying coil of wire suspended by a spring above the magnet. In the configuration shown, the north pole of the magnet is up and the direction of the current in the coil is clockwise as viewed from above. The coil of wire is repelled by the magnet and tends to "float" on the magnetic field of the magnet.

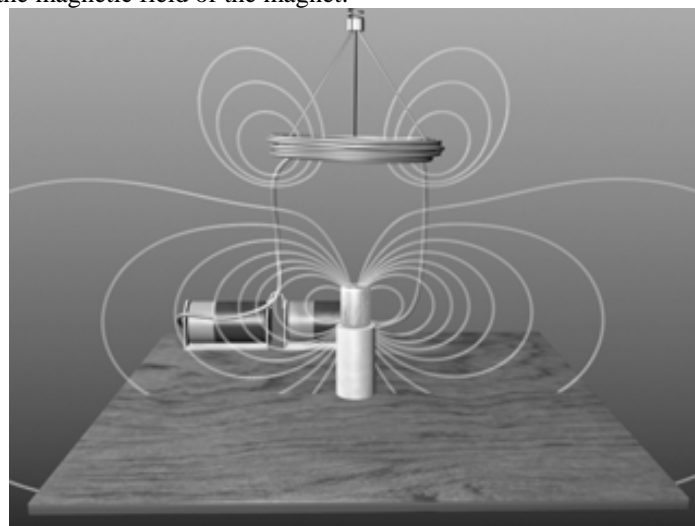


Figure 3. A passive visualization showing magnetic fields generated by a floating coil  
<http://web.mit.edu/8.02T/www/802TEAL3D/visualizations/magnetostatics/floatingcoil/floatingcoil.htm>

The second example in magnetostatics is an interactive one (see Figure 4). This Java 3D visualization also illustrates the forces on a current carrying coil sitting on the axis of a permanent magnet. For current flowing in



one direction in the coil, the force on the coil will be upward. If the current is strong enough, the coil will levitate, floating on the magnetic fields of the coil plus the magnet. This is the way one form of the Magnetic Levitation (MagLev) train works. For the other direction of current, the coil is attracted to the magnet.

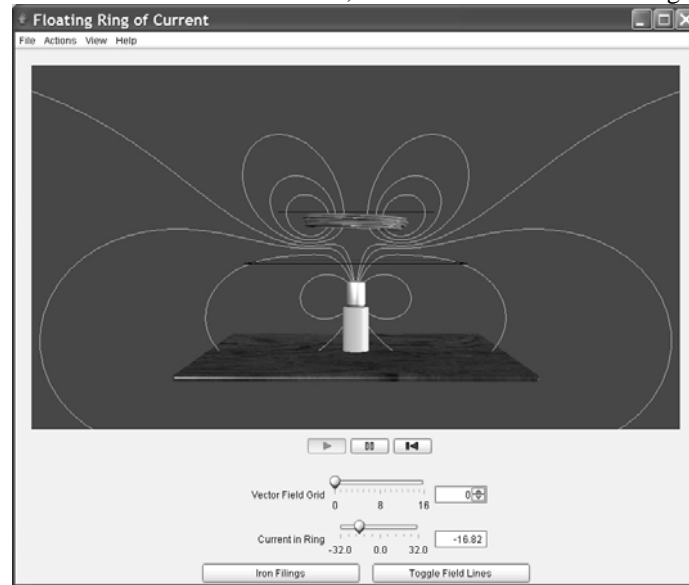


Figure 4. An interactive 3D visualization showing magnetic fields generated by a floating coil <http://web.mit.edu/8.02T/www/802TEAL3D/visualizations/magnetostatics/floatingcoilapp/floatingcoilapp.htm>

The user interacting with the Java applet 3D visualization shown in Figure 4 can vary the amount of current flowing in the coil. A related homework problem asks the student to calculate the amount and direction of the current necessary to get the coil to levitate above the magnet at a given distance. This calculation mimics a real experiment that the students do in class, where they directly observe the levitation of the coil in this circumstance.

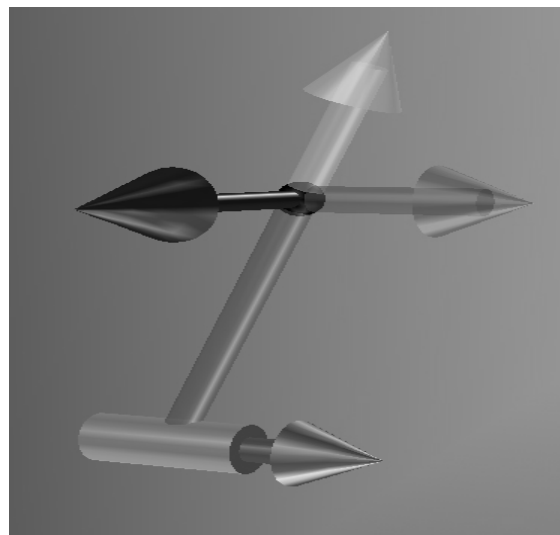


Figure 5: An interactive visualization of a magnetic field generated by a single current element

<http://web.mit.edu/8.02T/www/802TEAL3D/visualizations/magnetostatics/CurrentElement3d/CurrentElement.htm>

A Shockwave interactive visualization of the Biot-Savart Law in Figure 5 shows a magnetic field that a single current element generates. The top arrow pointing to the left represents the magnetic field generated by the current element (the bottom cylinder) at the observation point (the black sphere at the intersection of the three arrows). The observation point can be moved using keyboard arrow keys to sample the field at different positions relative to the current element. The bottom arrow at the current element and the top, right-pointing arrow at the



observation point indicate the direction of current flow. The upward-pointing arrow at the observation point indicates the direction from the current element to the observation point. By left-clicking and dragging in the window, the student can change the perspective of the view to get a sense of the 3D properties of this construction.

Figure 6 is another Shockwave interactive visualization, this time of the magnetic field generated by a ring of current. This visualization demonstrates the Biot-Savart Law applied to many current elements. By the principle of superposition, a continuous current distribution can be thought of as the sum of many discrete current elements (30 in this case). The large arrow in Figure 6(a) whose tail is at the observation point (black sphere) shows the total magnetic field at that point. The total field is the sum of the fields due to each element of the ring of current, represented here by the small vectors attached to the observation point. As Figure 6(b) shows, by shift clicking on any current element, the student can change the shading of both that current element and the field that it produces at the observation point. This helps identifying the contribution of that current element to the total field at the observation point. By left-clicking and dragging in the window, the student can change the perspective of the view to get a feel for the 3D properties of this assembly.

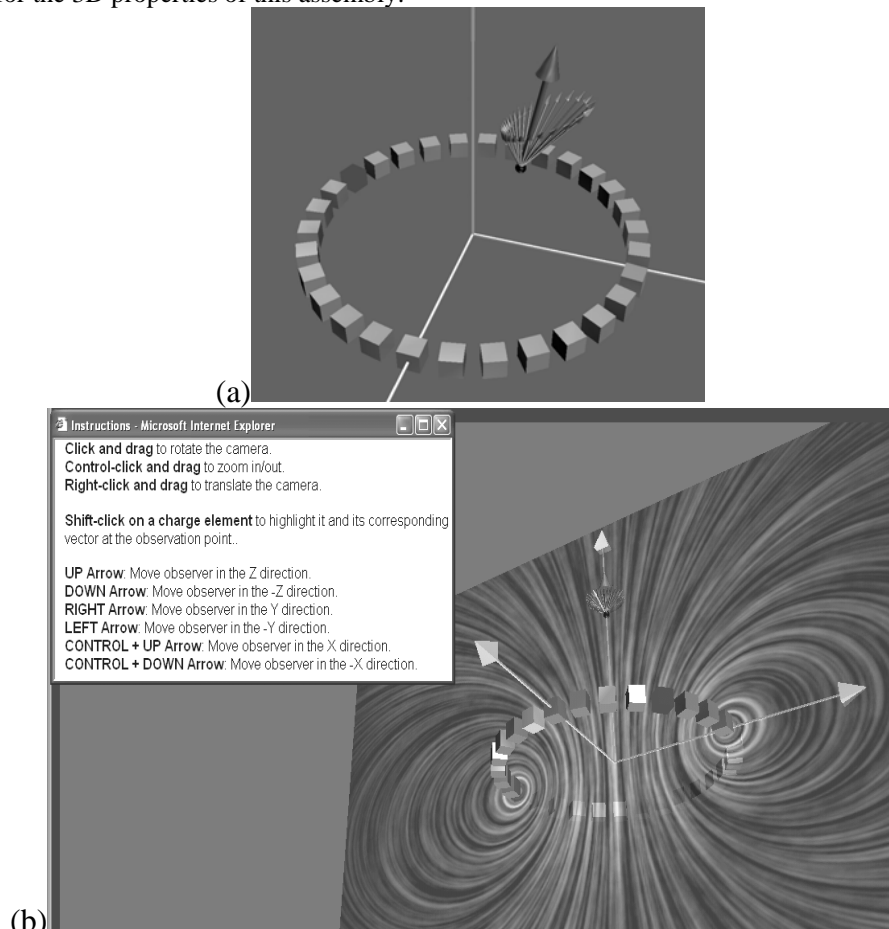


Figure 6. An interactive visualization showing the magnetic field generated by a ring of current <http://web.mit.edu/8.02T/www/802TEAL3D/visualizations/magnetostatics/RingMagField/RingMagField.htm>

Figure 7 is another interactive visualization, this time of Faraday's Law. The magnetic field in this JAVA applet is generated by a permanent magnet and by the current in an isolated coil of wire made of conducting non-magnetic wire (e.g., copper) that falls along the axis of the magnet. The only current in the coil is due to eddy currents arising in the coil as a result of the time-changing magnetic flux through the coil as it falls past the permanent magnet.

The student can vary both the total resistance of the coil of wire and the magnetic dipole moment of the magnet. The frame above is taken after a coil of fairly large resistance has fallen past the magnet from above. The curve in the graph box is the current in the wire as a function of time. The time profile here matches closely the time profile of an experiment that the students carry out in class to illustrate Faraday's Law.

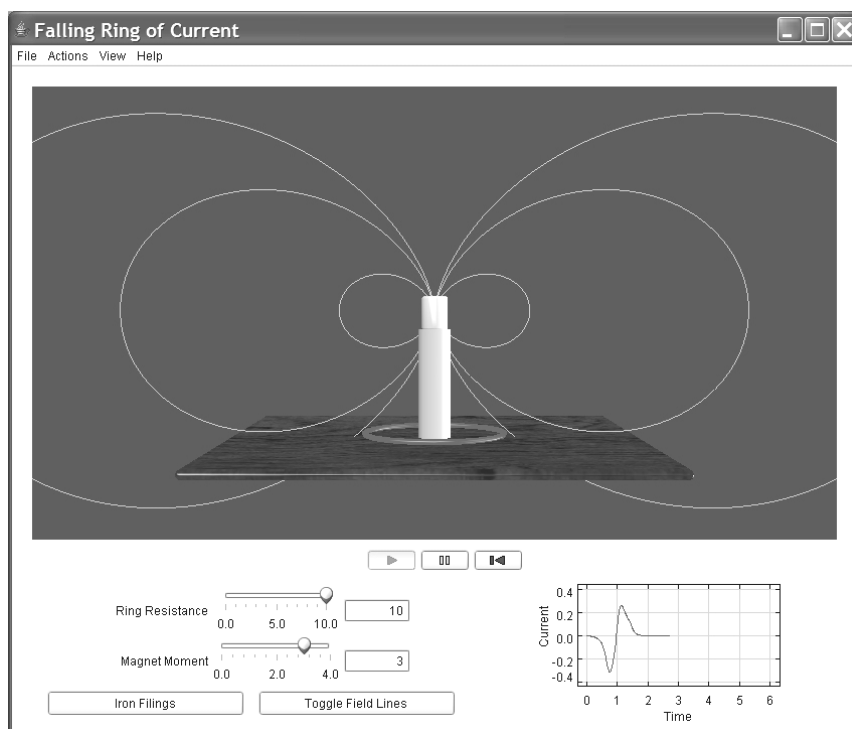
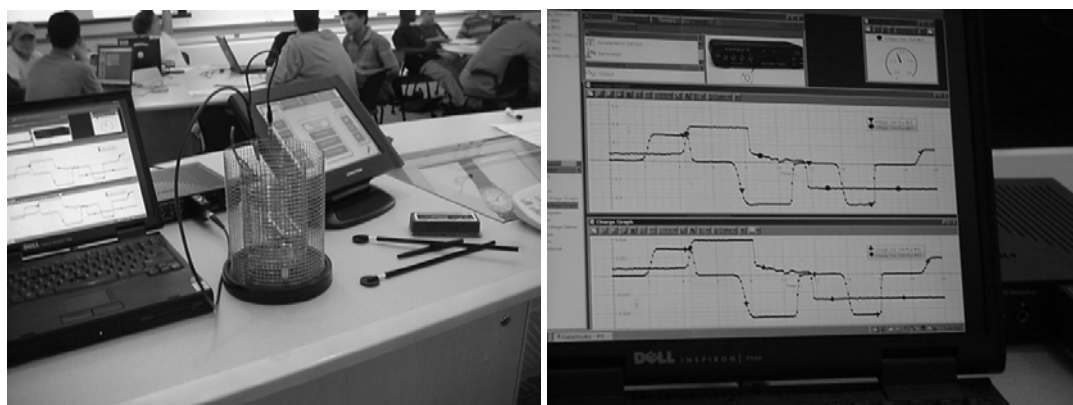


Figure 7. Farady's Law interactive visualization – the Falling Coil applet  
<http://web.mit.edu/8.02T/www/802TEAL3D/visualizations/faraday/fallingcoilapp/fallingcoilapp.htm>



(a) (b)  
 Figure 8. Faraday Ice Pail desktop experiment

Finally, returning to the subject of electrostatics, Figure 8 is an example of a hands-on desktop experiment dealing with electrostatic induction. The visualization here is of the data collected in the experiment (Figure 8(b)) when the student moves charged paddles in and out of the “Faraday” pail (Figure 8(a)). The two paddles are first rubbed against each other to produce electrostatic charges and are then put into the Faraday pail. The attached charge sensors measure the outer charge distribution that shows up on the laptop screen (Figure 8(b)).

#### FINDINGS - QUANTITATIVE LEARNING OUTCOMES OF THE TEAL PROJECT

We carried out a study that focused, among other factors, on students' learning outcomes and their perceptions about the visualizations and how they help to comprehend abstract concepts. The educational impact of the TEAL project was assessed using conceptual tests and a perception questionnaire. Results from students who took the TEAL Spring 2003 course (the experimental group) and Spring 2002 course (the traditional E&M course, the control group) are reported in detail by Dori and Belcher (2004). To underscore the contribution of the visualizations to the TEAL project students, we next briefly present the main findings of the assessment.

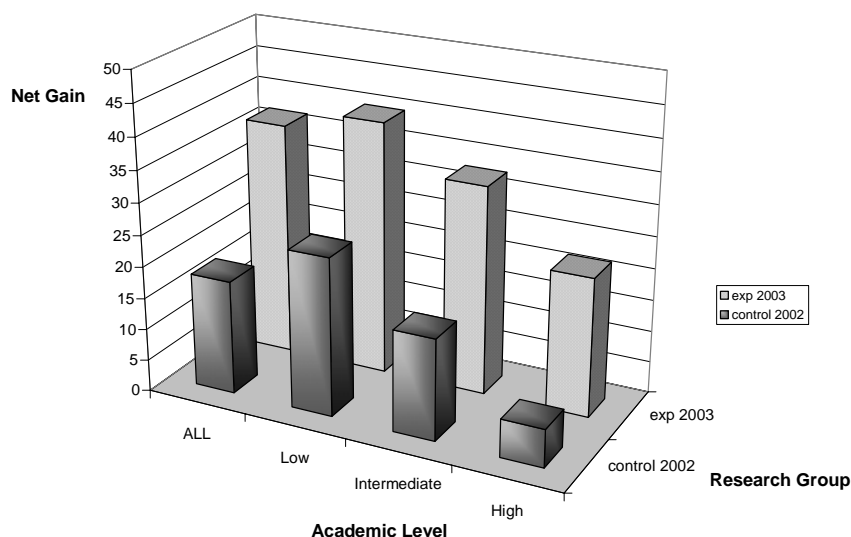


Figure 9. Students' net gain scores in the conceptual tests by academic levels for Spring 2003 experimental group – TEAL course (N= 514) and Spring 2002 control group – traditional course (N= 121)

The TEAL Spring 2003 course included about 600 students and six new instructors, who were not part of the development team (Belcher, 2001; Dori & Belcher, 2004; Dori et al., 2003). 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. The control group of Spring 2002 consisted of 121 students who took the traditional on-term E&M course, which was based on traditional lectures with demonstrations in a large lecture hall and smaller recitation sessions. The control group students were volunteers who were asked to respond to the pre- and posttests for monetary compensation.

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 and the control 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, 2004). Figure 9 presents the net gain results of the conceptual tests of both experimental and control groups. 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 strongly 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., 1999; 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 (Serway & Beichner, 2000). 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 (see Table 1) 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.

Table 1. Sample of 2003 experimental students' explanations to their selection of the various teaching methods

<i>Teaching method</i>		<i>Student's explanation</i>
Oral explanations by the professor		"Having teachers at our disposal for when we have questions with specific problems is possibly the best aspect of TEAL."
Technology	desktop experiments	"Desktop experiments help to really grasp the conceptual background of various problems while integrating calculations and quantitative analysis."
	2D & 3D 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 3D visualizations are the one thing that I can't get from a book or learning on my own." "Visualizations and conceptual questions help explain what is really happening behind all the numbers, especially in an abstract topic as magnetostatics."
	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 with PRS	"PRS was the best part of class because it took general concepts and shrunk 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."
	home problem sets	"The problem sets offered the main opportunity to connect material presented in class and figure out how it related to actual material covered on exams."
Written problems	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."
	Textbook	"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. "

#### FINDINGS - CLASS DISCOURSE WITH VARIOUS TYPES OF VISUALIZATIONS

Having presented several examples of visualizations using various techniques and their objectives, as well as quantitative results of TEAL students' learning outcomes, in this section we turn to a description of class discussions. The discourse, which took place while students were engaged in viewing and manipulating various visualizations, gives the flavor of diverse types of students' engagements with visualizations. It also provides some explanations as to how the learning outcomes were achieved.

The first example is related to visualization of a single current element based on Biot-Savart Law. This visualization is designed to encourage students to apply the right hand rule to determine relations between the directions of current and the magnetic field it produces. The second example is a magnetostatics experiment, in which a magnetic field is created by a permanent magnet. The students are asked to predict and draw a graph of the field of that magnet. They then use a Hall Probe to measure and verify or refute their prediction.

Next, we describe a brief "mini-lecture" demonstration of magnet levitation. Finally, an audio demo is described, in which students can hear the difference in signal strength when the orientation of two coils is changed so that their magnetic flux linkage goes from large to zero.

##### *Demonstration of the Biot-Savart Law for a single current element*

The professor began the session by providing an explanation of the electric field of a point charge and then drawing an analogy to magnetic field of a current element using PowerPoint slides. Students are quiet, some look at printouts of slides.

Professor: *OK, we're going to look at a visualization of the magnetic field generated by a current element.*

[Some students navigate on their laptops to the visualization, a Shockwave application that demonstrates the Biot-Savart Law for a single current element (see Figure 5).]

Professor: *This is the current element. Out in space, it will create a magnetic field.* [Draws vector out to a point] *Then it takes the cross product at the observation point. If I move this vector that goes out to the observation point, then it gives me the field. Watch what happens when I cross this point.* [Demonstrates on screen]. *It changes direction. This is not very intuitive so people have a hard time with it.* [Navigates back to lecture slides]. *If you look at the Biot-Savart visualization, we can look at what was going on.* [Students act out right hand rule with hands, similar to what is shown in Figure 10]. *Now let's talk about the force on a current-carrying wire in a magnetic field. This is our desktop experiment for today. First let's look at a simulation of what we expect when we put a coil of wire carrying current in the field of a strong permanent magnet, like what you have in the experiment.* [Demonstrates on screen first the passive visualization of Figure 3, then the interactive visualization of Figure 4. Some students watch these visualizations on their laptop screens while others look at one of the many large screens surrounding the classroom.]

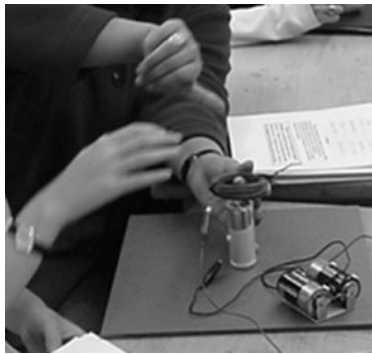


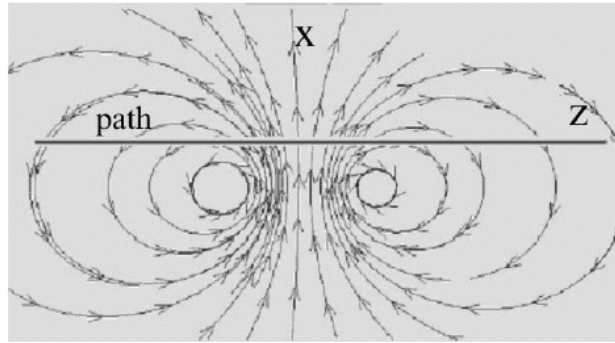
Figure 10. Students acting out the right hand rule

[Students watch the visualization, use right hand rule to determine forces, some play with the applet on the laptops. Visualization gets more attention than the slides.]

Professor: *Now let's do the real experiment with a real loop of current. Use your batteries* [Students carry out experiment illustrated in Figure 9 and get the coil to be either attracted or repelled by the magnet, depending on the direction of the current.]

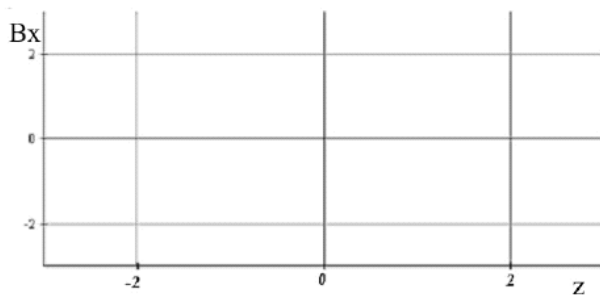
#### *Magnetostatics experiment: Magnetic field due to a permanent magnet*

After exploring the force between the current-carrying coil and the magnet in the above experiment, the class turns to a more detailed look at the magnetic field of the current-carrying coil of wire. They first use the Shockwave visualization in Figure 6 to explore virtually how this field is generated. They then use a Hall Probe and make measurements near the actual coil in predetermined ways. In addition to the Hall Probe, they also have a current sensor that measures the current through the coil. Before making the measurements, they are asked to predict what signal they would see. One of the predictions they are asked to make is shown in Figure 10.



**Figure 6** The magnetic field lines of a single coil of wire.

**Prediction 7** (*answer on your tear-sheet at the end*): Suppose you move from left to right along the horizontal path indicated in Figure 6 above. Predict the behavior of the *x*-**component** (i.e. the vertical component) of the magnetic field as you move along that path, and draw it in the panel of Figure 7 and on your tear-sheet at the end.



**Figure 7** Your prediction of the behavior of the *x*-**component** (the vertical component) of the magnetic field as you move along the path shown in Figure 6.

Figure 10. The worksheet used by students to predict the magnetic field of a current-carrying coil of wire

Student B: [reading] *Predict magnetic field as you move along the path using the drawing.* [Refers to Figure 10]. *Well it goes negative to zero to positive. See, it's going to get stronger and then weaker.*

Student A: [thinks about this]

Student B: [draws out his prediction]

Student A: *That's convenient.*

Student B: *Well, it looks really weird but... Well, I definitely know it is zero here.*

[Student A looks skeptical, Student B explains his drawing more].

[Students start measuring].

Student A: *How do we measure this?*

Student B: *With these graphs.*

Student A: [reads] *with the current sensor.*

Student B: *Do we need the current sensor?*

Student A: *yeah.*

Student B: *So do we need this thing?*

Student A: *We need both.* [reading] *Usually it tells you. Put that in series with the sensor.*

Student B: [plugs in wires] *So this goes in here?*

Student A: *yup.*

Student B: *OK.*

Student A: *Wait [pointing]—this is the current sensor, right?*

Student B: *Yes.*

Student A: *Then it goes in here.*

Student B: *X-direction or Radial on the current sensor?*

Student A: [Looking at handout]. *It says radial.*

Student B: *OK. Good decision.*

Student B: *OK [reading] "Measure the vertical component of the magnetic field. Make sure the white dot is up."*

Student A: *Let's just see how it goes. [They begin testing].*

Student B: *Shouldn't the current be the same?*

Student A: *The current is changing.*

Student B: *Maybe we have our things switched.*

Student A [turning to the laptop]: *Stop making me mad! [to Student B] I love how they tell us one thing and it is really another.*

Student B: *I know. Do we need to calibrate it?*

[Student A moves sensor across coil, they watch the graph being drawn on the laptop screen. A & B are puzzled by resulting graph].

Student B: *Is that what we just did?*

Professor [to class]: *If you haven't made a measurement, raise your hand.*

Student B: *Don't worry about the numbers, just the slope matters [then consults with a neighboring group about their results].*

Student A: *I think it was right.*

Student B: *If we keep going out, it would get small again.*

### ***Magnet levitation demonstration***

This is a brief transcript of a magnet levitation demonstration. Students can watch a movie of this demo on the Web as well.

Professor: *We start with a magnet levitation demonstration: A small magnet levitates above a superconducting disk in liquid nitrogen. [This is the rare earth magnet levitating above the high temperature super-conductor, see Figure 11]. There are applications in magnetic levitation trains in Japan and France.*





Figure 11. A rare earth magnet levitating above a high-temperature superconductor in a bath of liquid nitrogen

Student F: [upon seeing magnet levitate] *Wow—that's cool!*

Professor: *So we're using liquid nitrogen with a high temperature superconductor. At a low temperature, the resistance goes to zero. So I am taking the magnet and putting it here above the conductor with absolutely zero resistance.*

#### *Coil-radio mutual inductance audio demonstration*

A radio amplified is hooked up to a large coil of wire. A second coil, placed near the first one, is connected to loudspeakers, with the two coils facing one another. The professor turns on the radio, and a commercial is suddenly audible in the room. When the professor rotates one of the coils by 90 degrees with respect to the other coil, the voice is silenced. The abrupt end of the cookie commercial gets a big laugh from almost all of the students.

Professor: *So you see the effect of mutual inductance.*

Student H: *Maybe they should have explained that the radio was related to the demonstration.*

[Professor does the demonstration again, and students laugh at the sudden end to the voice again.]

Professor: *By rotating the coil, the signal is not received.*

Summarizing the TEAL class discourse, it was apparent that the social aspect was an important factor in the construction of knowledge and contributed to establishing new insights and sharing knowledge with peers. The class discourse showed that the TEAL approach encouraged multiple-aspect interactions, including technical, affective, and cognitive. The transcript presented in this section illustrates an incremental shift in students' cognition from ambiguous, partially constructed knowledge to repaired, shared knowledge (Roschelle, 1992), much of which is gained through visualization, engagement with an MBL setting, and social interaction.

## DISCUSSION AND SUMMARY

Information and communication technology, as applied for instruction, has struggled with designing appropriate and effective learning environments for teaching science, especially at a higher education level. This chapter has focused on visualizations and simulations in undergraduate physics education and the value they may bring to elevating the level of deep understanding of the laws and phenomena in electricity and magnetism in particular. The visualizations included visual simulations (still and moving, 2D and 3D, active and passive computer-rendered images) and MBL (desktop experiments and the graphs produced) in physics education. In addition to describing the development and usage of these ICT-based means, we also investigated the value they may bring to elevating the level of deep understanding of laws and phenomena in physics in general and electricity and magnetism in particular.

Rieber (2002) discussed learning within computer-based simulations and brought up a key question of when to defer to instruction as an intervention. Presenting too much instruction with a simulation too soon may

strengthen the perception of science as accumulation of facts and principles and inhibit a student from discovery learning—using the scientific method to think like a scientist. However, most students are ill-equipped to handle the full discovery learning process without some level of support. Therefore, instructional intervention is a viable and desirable approach, along with suggestions during the use of simulation, as long as the teacher or the professor carefully chooses models and multiple representations and the order in which they are presented.

It is interesting to compare the level of visualizations in physics and chemistry. In chemistry (Russell & Kozma, 2004, in this book), visualizations have been extensively developed, applied and studied in the context of computerized molecular modeling. However, the MBL elements of visualizations in chemistry have not been investigated thoroughly. In physics, on the other hand, the situation is almost reversed. While MBL has been developed, applied and researched extensively (Kown, 2002; Lapp, 1999; Trumper & Gelbman, 2000), the other facet of visualizations, namely visual simulations, is much less prevalent. Most of the literature describes simulations in mechanics and the learning effects of some of these simulations were investigated with inconclusive results (e.g., de Jong et al., 1999; Steinberg, 2000; Hake, 1998). In electricity, fewer simulations exist and these are even less investigated in terms of their learning gains. In contrast to the TEAL outcomes, Escalanda and Zollman (1997) did not find significant differences in final exam scores between the participants in interactive digital video activities in introductory college physics course and the non-participants. However, as in the TEAL project, the researchers found that the majority of the participants felt that the activities and the visualizations were effective in helping them learn the physics concepts studied in that course.

The TEAL project has been described in detail since it focuses on electromagnetism and incorporates both visual simulations and MBL. The research outcomes of the TEAL project indicate that students significantly improved their conceptual understanding of the subject matter since they were engaged in high levels of interaction, as can be seen from the class discourse above. The results strongly suggest that the learning gains in TEAL are significantly greater than those obtained by the traditional lecture and recitation setting. The positive results are consistent with several studies of introductory physics education over the last two decades (Beichner et al., 1999; 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%).

While Brasell (1987) emphasized the importance of real-time analysis with microcomputer-based laboratory tools, Brungardt and Zollman (1995) demonstrated through qualitative and quantitative data that the simultaneous-time effect in videodisc activities is not a critical factor in improving student learning of kinematics while using their graphing skills. However, they found that students were aware of the simultaneous-time effect and seemed motivated by it: students decreased eye movement between computer screen and video screen as subsequent graphs were produced, and demonstrated more discussion during graphing than delayed-time students. Russell, Lucas & McRobbie (2004) claimed that positive research findings in support of MBL activities facilitating science learning can be explained in terms of the increased opportunities for student-student interactions and peer group discussions about familiar events.

Some of the inconclusive results in the literature regarding the effect of rich visualization environments on cognitive skills can be explained by Bonham, Deardorff and Beichner (2003) who claimed that the change in the medium itself has limited effect on student learning. Their research findings indicate that although web-based homework affects the nature of feedback students received, there was no significant differences between students who used web-based homework and those who used paper-based homework - when comparing students performance on regular and conceptual exams, quizzes, laboratory and homework.

When educational technology is intertwined with social interaction and proper mentoring, improvement in both the cognitive and affective domains can be achieved not only for middle and high school science education, as shown in previous studies (Blumenfeld Fishman, Krajcik, Marx & Soloway, 2000; Barnea & Dori, 2000; Dori, Sasson, Kaberman & Herscovitz, 2004; Elyon, Ronen & Ganiel, 1996; Krajcik, 2002; Linn, 1998), but also in undergraduate chemistry (Adamson, Nakhleh & Zimmerman, 1997; Dori, Barak & Adir, 2003; Kozma, Chin, E., Russell, J., & Marx, 2000) and physics education (Dori & Belcher, 2004).

As Lee, Nicoll, and Brooks (2004) indicated, students tend to approach physics mathematically, not conceptually, when they work on traditional textbook problems. However, they think about phenomena conceptually before making calculations when they interact with problems in a visualizations setting. More studies are needed to further establish the educational value of the various types of visualizations for teaching physics in general and electromagnetism in particular.

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