The Physics Department at MIT is introducing a new format for teaching introductory mechanics (8.01) and electricity and magnetism (8.02) courses in the fall of 2001. This offering is being developed under Departmental guidance and by the TEAL/Studio Physics Project, which is an outgrowth of initiatives sponsored by the MIT Council on Educational Technology.[1] The project is funded by the d'Arbeloff Fund for Excellence in MIT Education,[2] iCampus,[3] the National Science Foundation (NSF),[4] and a variety of other sources.[5] "TEAL" stands for Technology Enabled Active Learning, and "Studio Physics" loosely denotes a format instituted in 1994 at Rensselaer Polytechnic Institute by Professor Jack Wilson, now directed by Professor Karen Cummings. This pedagogy has been modified and elaborated on at a number of other universities, notably in North Carolina State University's *Scale-Up* program, under Professor Robert Beichner. In this article, we describe what is being done, and why.

John W. Belcher

Studio Physics at MIT

Objectives

Before launching into the details, what do we hope to achieve? The first goal is the reintroduction of hands-on experiments into the large freshman introductory courses. Physics is an experimental science, but with the notable exceptions of 8.01X/8.02X, courses with simple take-home experiments, and 8.012/8.022, tailored for physics majors, we have no hands-on laboratories in our introductory courses. The standard complaint about laboratories is that the experiments are disconnected from the course material and too "cookbook" in nature. As we describe below, the studio format has the advantage that it incorporates the experiments into the flow of the course material, and allows for student discussion and reflection on the significance of the experiments in context.








Our first TEAL course will be 8.02 and we show in *Table 1* some of the experiments that will be done this fall. Three of these are adopted directly from the 8.02X suite of experiments created by Professor Emeritus John King. Others are standard experiments from makers of commercial desktop experiments such as PASCO and TeachSpin. The number of experiments will undoubtedly grow as the course matures. For some of the desktop experiments, there is a data acquisition link between the experiments and laptops. We are using the PASCO 750 Interface for analogue to digital conversion, and Data Studio software for data analysis and display. The 750 Interface has both a signal generator and associated oscilloscope software for use in, for example, LRC circuit experiments.

The second goal of TEAL/Studio is to engage students more fully in the introductory courses by using "active engagement" methods in addition to lecture.[6] Even with an outstandingly effective and charismatic lecturer like Professor Walter Lewin, lecture attendance at the end of the term in our introductory courses hovers around 50%. No matter how strongly one feels about the intrinsic worth of the lecture format,[7] it is hard to argue that it is broadly effective when half of the students do not attend the lecture. This lack of student engagement is arguably one of the major reasons for the failure rates (typically 15%) in these introductory courses. More importantly, this lack of engagement is the reason many students leave our introductory courses (usually their last courses in physics) feeling that physics is dry and boring. In considering the description of the TEAL/Studio course format below, keep in mind that one of the overall goals

• Experiments in TEAL/Studio Fall 2001 •
Electrostatic Charge Sticky Tape Experiments
Vector Fields and Superposition
Electrostatic Charge with Faraday Ice Pail (PASCO)
Electrostatic Force (from 8.02X: determines ε_o experimentally)
Ohm's Law
RC Circuit
Field of Magnet (with PASCO's dual-axis Hall Probe)
Levitating Coil (using a magnet with a surface field of 6 KG)
Magnetic Force (from 8.02X: determines μ_o experimentally)
Magnetic Force On A Dipole ($\mu \cdot \nabla B$ force from TeachSpin)
Faraday's Law (using a magnet with a surface field of 6 KG)
LR Circuit (using PASCO's oscilloscope software)
Transformer
LRC Circuit (using PASCO's oscilloscope software)
Microwave (from 8.02X: a spark gap microwave generator)
Single/Double Slit Interference (using a pocket laser)
Light Intensity Falloff

TABLE 1

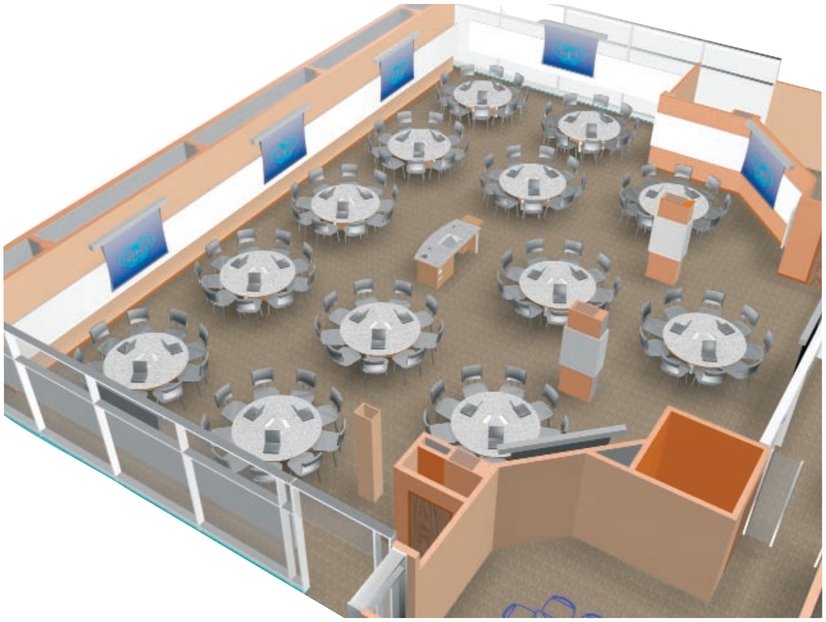

FIGURE 1

The TEAL/Studio Physics Classroom

is to set up a structure that engages the students more deeply, so that they come away from these introductory courses with more of an appreciation for the beauty of physics, both conceptually and analytically.

Pedagogy

The first thing that is different in the TEAL/Studio format is that it requires very different space for instruction. *Figure 1* shows a 3D rendering (by Mark Bessette, the TEAL/Studio 3D illustrator/animator) of the space we are using in the fall of 2001.[8] *Figure 1* shows 13 tables with seven-foot diameters on fourteen-foot centers. With nine students at a table, this room design accommodates 117 students. The instructor's station in the center of the room is used to present instructional material (projected on eight projection screens around the perimeter of the room) and to demonstrate large experiments that are not appropriate for the desktop. The instructor's station has both three-phase AC power, as well as DC power, for use in some of the more specialized large demos. There are numerous white boards around the perimeter of the room for impromptu discussions and presentations by staff members to students, and by students to students. What is going on at these whiteboards can be captured by video cameras and projected onto the perimeter screens, if desired (for example, for group reports).

The basic idea of the studio classroom is to merge lecture, recitation, and hands-on laboratory experiments into a single common experience. Short intervals of formal instruction are interspersed with the desktop experiments (one experimental setup per group of three students) and collaborative work in groups (one networked laptop per group of three students). The groups of three are formed at the beginning of the term and last throughout the term. Dr. Lori Breslow of MIT's Teaching and Learning Laboratory (*http://web.mit.edu/tll/*), who has experience across the Institute with effective practices in collaborative learning, guided us in the setup of the collaborative structure of the course. A class meets for five hours per week in the TEAL/Studio (for example, two hours on Monday and Wednesday, and one hour on Friday). In the fall of 2001, our first experiment will be to teach 8.02 in two sections of about 70 students apiece. For this initial effort, the staffing is somewhat higher than in steady state. Professor John Belcher, Dr. Peter Dourmashkin, Professor David Litster, and Dr. Alan Lazarus will teach these two sections, along with two graduate teaching assistants, technical instructors, and undergraduate help.

We are also using an automated system for submission and electronic grading of problem sets (WebAssign, located at *http://www.webassign.net*), with assignments due on the evenings before days with class sessions. Problems in the assignments are both on material to be covered in that next day's class (more qualitative) and on material covered in previous classes (more quantitative). This insures that students have some familiarity with the material to be covered before they walk into the class. The instructor thus has the freedom to cover material that is more sophisticated, rather than spending time covering definitions and straightforward concepts that can easily be picked up by reading the text. There is an additional feature of this system, in that WebAssign gives the instructor access to a summary of how the students did on an assignment just after the submission deadline. This allows for "just-in-time" changes in emphasis for material covered in the next class.

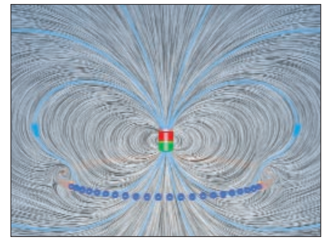

FIGURE 2

One frame of an animation of a magnet falling through a conducting non-magnetic ring, with two different representations of the magnetic field.

FIGURE 3

One frame of an animation showing the electric field lines of the 8.02X microwave experiment antenna. The antenna is sitting on one of the tables in the TEAL/Studio classroom.

Visualization

In going to the studio format, we are benefiting from the experience of many institutions outside of MIT that have pioneered that format. The challenge is to adapt it to the unique set of capabilities of the MIT student body. In addition to this adaptation of existing instructional models, there is also a research component of TEAL/Studio. This component centers around developing new approaches to teaching physics and evaluating their effectiveness. For electromagnetism, the research focus is on the use of modern visualization techniques to help students understand fields and their effects.

Electromagnetism is a notoriously difficult subject for beginning students.[9] Visualization, especially animations, allows the student to gain insight into the way in which fields transmit forces, by watching how the motions of material objects evolve in time in response to those forces. Such animations allow the student to make intuitive connections between forces transmitted by electromagnetic fields and forces transmitted by more prosaic means, e.g., by rubber bands and strings. The TEAL/Studio Project is developing a number of simulations and visualizations along these lines, many of them suggested by the desktop experiments. This development is under the supervision of Andrew McKinney, TEAL/Studio Project Manager at the MIT Center for Educational Computing Initiatives (CECI). CECI is a unit of the MIT Center for Advanced Educational Services (*http://www-caes.mit.edu/*).

As an example of this approach, *Figure 2* shows one frame of an animation of the magnetic fields of a permanent magnet falling through a conducting non-magnetic ring. We show representations of the field using both field lines and also using a much more highly detailed representation, Line Integral Convolution (LIC),[10] introduced in 1993. In recent research sponsored by TEAL/Studio, we have developed a novel method for animating the LIC tech-

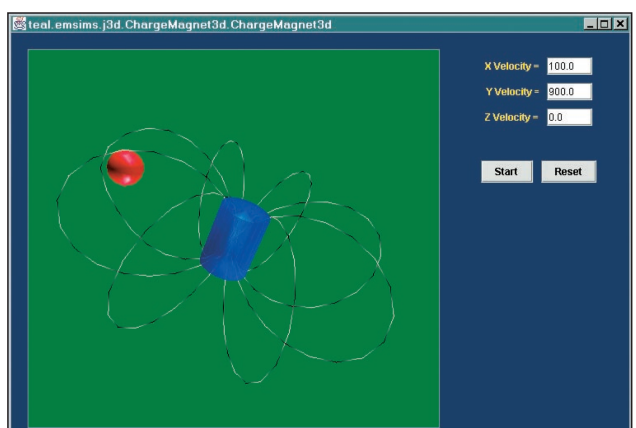

FIGURE 4

A Java 3D applet showing the motion of an electric charge in the magnetic field of a magnetic dipole.

nique.[11] In other situations, we use animation for exposition of field line patterns alone with no dynamical implications. For example, *Figure 3* shows the electric fields from the 8.02X microwave experiment antenna (which is a quarter-wave antenna). This is one frame of an animation that shows the pattern of the emitted radiation over the full cycle.[12]

In addition to these passive visualizations, TEAL/Studio is developing Java applets[13] (for example, see *Figure 4*) that are interactive, and which illustrate many concepts in electromagnetism. As a measure of the speed of modern laptop machines, it is worth noting the applet illustrated in *Figure 4* calculates the motion of an electric charge in the field of a magnetic dipole, and also calculates field lines for the total magnetic field (due both to the moving charge and the dipole), using 4th order Runge-Kutta schemes. The applet then displays the field lines in a 3D rendering rapidly enough to make the motion of the charge and the field lines appear as a smooth real-time animation.

Assessment and Evaluation

It is vital to have a built-in assessment process that accompanies the development and implementation of a project such as the TEAL/Studio Project. The assessment effort for TEAL/Studio is under the direction of Professor Judy Dori of CECI, on leave from the Technion, Israel. We began the assessment process in the fall 2000 8.02 class.[14] Although taught in the lecture/recitation format, we included five desktop experiments in the recitations, as well as on-line applets and visualizations. Student performance in the course was investigated using quantitative problems typical of the freshman level, multiple choice conceptual pre- and post-tests, open-ended conceptual questions, and surveys over the term of preferences for the various teaching methods used. As an example of some of the results of this assessment, *Figure 5* shows the correlation between the pre-test results in 8.02 fall 2000 (multiple choice and conceptual, given in the first lecture) and a measure of the overall student performance in the course (primarily based on quantitative questions on in-class exams). To the extent that the pre-test is predictive of overall performance in the course, these results both validate the pre-test (i.e., it is measuring something we want it to measure) and allow us to use the pre-test at the outset in future classes to predict those students who may need additional help. These evaluation instruments are being used again this fall in the full TEAL prototype, and they will serve as a baseline to measure the success of the studio approach as we go forward.

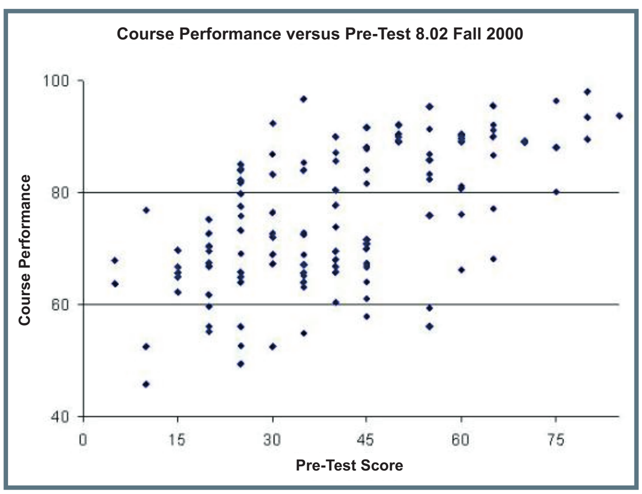

FIGURE 5

Course performance versus pre-test score for 126 students in 8.02, fall 2000, showing that the pre-test score (given during the first class) is somewhat predictive of overall performance in the course.

What Comes Next

Assuming that the prototype offering of TEAL/Studio this fall is successful, we will revise the course structure and materials in the spring and summer of 2002, based on what we learn this fall, and give the course again in the fall of 2002. The plan is to move this mode of instruction into on-term 8.02 in the spring of 2003, with about 600 students. This will require six sections of the course, utilizing the classroom above full time (expanded by two tables to accommodate 117 students per section). The staffing at this point will be one faculty member and two teaching assistants for each group of 100 or so students. These staffing levels are about the same as what the Department currently uses in the lecture/recitation format of on-term 8.02, which is a baseline constraint. The goal is to change the mode of instruction in 8.02 from the traditional lecture/recitation format to the interactive TEAL/Studio mode, with a steady state cost that is the same as the present lecture/recitation mode of instruction, exclusive of start-up costs. Assuming the large-scale 8.02 experiment in the spring of 2003 is successful, this format will be extended to 8.01 in the fall of 2003, beginning with one of the smaller versions of 8.01 offered that fall, such as 8.01X. Assuming success in this as well, the plan is to offer all of the introductory physics courses in the TEAL/Studio format, with the exception of 8.012 and 8.022, by the fall of 2004.

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ENDNOTES

1 MIT Provost Professor Robert Brown, EECS Professor Hal Abelson, and Dean of Undergraduate Education Professor Robert Redwine are Co-Chairs of the MIT Council on Educational Technology. The purpose of the Council is to provide strategic guidance and oversight of MIT efforts to develop an infrastructure and initiatives for the application of technology to education (see *http://web.mit.edu/cet/*).

2 The d'Arbeloff Fund for Excellence in MIT Education is a program to maximize the value of MIT campus-based learning by the creation of new approaches to higher education supported by emerging information technologies. The fund is supported by a grant from Alex and Brit d'Arbeloff (*http://www-tech.mit.edu/V119/N11/donation.11n.html*).

3 iCampus is the MIT/Microsoft Alliance, a joint effort between MIT and the Microsoft Corporation to develop and evaluate new ways to use technology in education.

4 NSF Grant #9950380, "Force Field: Using Animation in Teaching Electromagnetism," John Belcher, Markus Zahn, and Janet Murray, Principal and Co-Investigators.

5 The Helena Foundation, Alumni Funds from the Classes of 1951 and 1955, and the MIT Class of 1960 Fellows Program, the MIT School of Science's Educational Initiative Awards, and MIT Academic Computing.

6 E.F. Redish, "New Models of Physics Instruction Based on Physics Education Research." Invited talk presented at the 60th meeting of the Deutschen Physikalischen Gesellschaft, Jena, 14 March 1996, on-line at *http://www.physics.umd.edu/rgroups/ripe/papers/jena/jena.html/*.

7 David J. Griffiths, "Millikan Lecture 1997: Is there a text in this class?" *American Journal of Physics*, December 1997, 65 (12), pp. 1141-1143.

8 Overall coordination by the Office of the Dean of Undergraduate Education, Professor Robert Redwine, Dean, and the Registrar's Office. Thomas Tharp, MIT Project Manager; architectural design by Daniel Dyers of Miller Dyer Spears, Inc.; audio-visual design by Multimedia Systems Design in collaboration with MIT Audio-Visual Services; network infrastructure by MIT Information Systems; renovation by Shawmut Design and Construction.

9 In one of his first papers on the subject, Maxwell remarked that "To appreciate the requirements of the science [of electromagnetism], the student must make himself familiar with a considerable body of most intricate mathematics, the mere retention of which in the memory materially interferes with further progress…," J.C. Maxwell, "On Faraday's Lines of Force," Transactions of the Cambridge Philosophical Society, X, Part I (1855), as quoted by Thomas K. Simpson, *Maxwell on the Electromagnetic Field* (Rutgers University Press, New Brunswick, NJ, 1997), p. 55.

10 B. Cabral and C. Leedom, "Imaging Vector Fields Using Line Integral Convolution," Proc. SIGGRAPH '93, pp. 263-270, 1993.

11 Andreas Sundquist, "Dynamic Line Integral Convolution for Visualizing Electromagnetic Phenomena," MIT Master's Thesis in Engineering in Electrical Engineering and Computer Science, and Senior Thesis in Physics, 2001. Preprint of a paper based on this thesis is available at *http://web.mit.edu/jbelcher/www/DLIC.html*.

12 Mark Bessette is responsible for the construction of these animations using Discreet's 3ds max 4. For an explanation of the physics of such animations, see J.W. Belcher and S. Olbert, "Field Line Motion In Classical Electromagnetism," submitted to the American Journal of Physics, June 2001, available at *http://web.mit.edu/jbelcher/www/FLM.html*.

13 The Java applets are being developed at the MIT's Center for Educational Computing Initiatives. CECI is also responsible for the acquisition, networking, and maintenance of the TEAL/Studio laptops.

14 Yehudit Judy Dori and John Belcher, "Assessing The Technology Enabled Active Learning Project," Paper presented at the 2001 NARST Annual Meeting – the National Association for Research in Science Teaching Conference, St. Louis, MO, USA. March 25-28, 2001.