# Improving Students' Understanding of Electromagnetism through Visualizations – A Large Scale Study*

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*Abstract*

Science educators face a challenge of developing and implementing technology-rich learning materials and environments, especially in higher education. The Technology-Enabled Active Learning (TEAL) Project at MIT involves media-rich software for simulation and visualization in freshman physics. The objective of the project is to transform the way physics is taught in large enrollment physics classes at MIT in order to increase students' conceptual and analytical understanding and decrease failure rates in these courses. The approach is designed to help students develop better intuition about, and conceptual models of, electromagnetic phenomena. The reform is centered on an "active learning" approach – a collaborative, hands-on environment, with the use of desktop experiments, visualizations, web-based assignments, and a personal response system. The objective of the research is to assess cognitive outcomes of MIT undergraduate students who study electromagnetism in a large-scale TEAL setting and compare them with outcomes obtained in small-scale TEAL and traditional settings. We compared three groups: small-scale TEAL implementation, large-scale TEAL implementation, and traditional setting. Our study establishes that the TEAL-studio format has a significant and strong positive effect on the learning outcomes of MIT freshmen. The TEAL format enhanced the students' ability to transfer electromagnetic concepts from abstract to concrete.

*Introduction*

Science educators face a challenge of developing and implementing technology-rich learning materials and environment, especially in higher education. In the domain of electromagnetism such technology-rich environments are even more crucial, as they can enable the presentation of spatial and dynamic images and portray relationships among complex concepts. The Technology-Enabled Active Learning (TEAL) Project at MIT (Belcher, 2001; Dori & Belcher, 2003) involves media-rich software for simulation and visualization in freshman physics. The objective of the project is to transform the way

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physics is taught at large enrollment physics classes at MIT in order to increase students' conceptual and analytical understanding and decrease failure rates in these courses. The approach is designed to help students visualize, develop better intuition about, and conceptual models of, electromagnetic phenomena. The reform is centered on an "active learning" approach – a collaborative, hands-on environment, with the use of desktop experiments, visualizations, web-based assignments, and a personal response system (PRS).

### *Theoretical Background*

During the past decade, a number of physics curricula for undergraduate students have been developed that utilize educational research outcomes. These include Physics by Inquiry and Tutorials in Introductory Physics (McDermott, 1991; McDermott & Shaffer, 2002), Workshop Physics (Laws, 1991), Tools for Scientific Thinking (Thornton & Sokoloff, 1990), RealTime Physics (Sokoloff, Thornton & Laws, 1999), Matter & Interaction (Chabay & Sherwood, 1999), Peer Instruction, (Mazur, 1997), Studio Physics (Cummings, Marx, Thornton & Kuhl, 1999), and Studio Physics Scale-Up (Beichner, 2002).

The common thread in all these college-level physics curricula is that they emphasize elements of active learning and conceptual understanding that build on making predictions, observing and discussing the outcomes with peers. However, many of the students resent having to "teach themselves" and prefer lectures. Instructors often need to face the challenge of switching from traditional modes to creative instructional strategies and experience difficulties in this process of breaking away from ways they had been taught (Laws, 1991).

Incorporating physics into an integrated freshmen engineering class, Beichner et al. (1999) found that the impact of the technology-rich, collaborative learning environment accounted for better performance of experimental students with respect to peers in traditional classes, often by a wide margin. Student satisfaction and confidence, as well as their retention rates, were remarkably high. While most researchers used mechanics as the subject matter in their studies, our study of the TEAL project is targeted at the freshmen electromagnetism course, with emphasis on visualization and conceptual understanding.

### *Research Objective*

The objective of the research is to assess cognitive outcomes of MIT undergraduate students who study electromagnetism in a large-scale TEAL setting and compare them with outcomes obtained in small-scale TEAL and traditional settings.

### *Research Setting*

The TEAL/Studio environment is a merger of lecture, recitations, and hands-on laboratory experience into a technologically and collaboratively rich experience for incoming freshmen. It is patterned in many ways after the Studio Physics effort of RPI (Cummings et al., 1999) and the Scale-Up effort of NCSU (Beichner, et al., 2002). TEAL improves upon these efforts by incorporating advanced 2D and 3D visualizations. In Fall 2001, as soon as the physical infrastructure for teaching the course in the Studio format was in place, we conducted our small-scale study. The TEAL learning space contains 12 round tables with 9 students seated around each table and working in teams of 3 on a laptop. 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. Such animations allow students to make an intuitive connection between the forces transmitted by electromagnetic fields and more tangible forces, such as those exerted by rubber bands or strings.

*Research Population*

The experiment started with a pilot study, conducted in Fall 2000 which served to validate the learning materials, the visualizations, and the assessment tools. This paper reports the results of a comparison of three groups: small-scale TEAL implementation, large-scale TEAL implementation, and traditional setting.

The small-scale experiment was conducted in Fall 2001 and included about 180 students. Two thirds of these students were upper classmen who failed either the mechanics course or the electromagnetism course. One third was comprised of freshmen who studied physics in high school at the advanced level and advanced placed the mechanics course. The students who took the traditional large lecture and recitations electromagnetism course of Spring 2002 served as the control group. This group consisted of about 120 volunteers, 90% of whom were freshmen and the rest were upper classmen. The large-scale experiment was conducted in Spring 2003 and included about 550 students, most of whom were freshmen. We divided the Fall 2001 population into three about equal parts, thereby defining three academic levels: high, intermediate, and low. The resulting pretest borderlines between academic levels were as follows: high academic level students scored above 45 out of 100 points, intermediate level students scored between 30 and 44, and low academic level students scored below 30. These borderlines remained the same for the control group in Spring 2002 and the second experimental group in the Fall 2003.

*Research Tools*

The assessment of the project includes examining students' conceptual understanding before and after studying electromagnetism in a media-rich environment. We developed pre- and posttests consisting of 20 conceptual questions from standardized tests (Maloney, et al., 2001; Mazur, 1997), as well as questions designed to assess the visualizations and experiments. The tests included open-ended (Bagno & Eylon, 1997) and multiple choice questions that require qualitative and quantitative responses. The research tools included also a survey and focus group discussions.

*Findings*

The failure rates in the experimental groups were 1% in the small- and large-scale experimental groups, compared with 13% in the traditional control group. Figures 1, 2 and 3 respectively present the conceptual test results of Fall 2001 small-scale experimental group, Spring 2003 large-scale experimental group, and Spring 2002 control group.

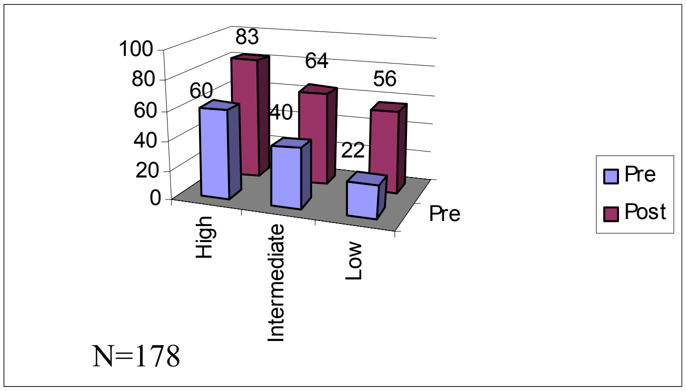


Figure 1. Fall 2001 small-scale experimental group results in the pre- and posttests

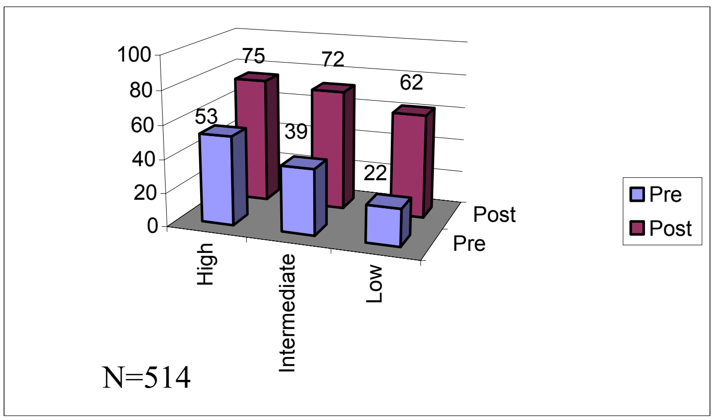


Figure 2. Spring 2003 large-scale experimental group results in the pre- and posttests

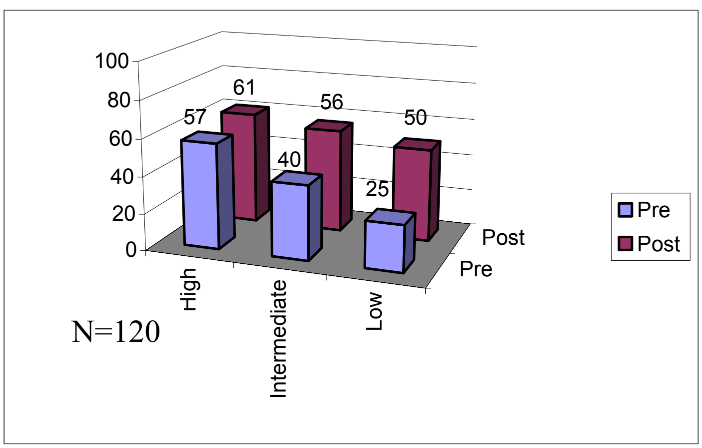


Figure 3. Spring 2002 control group results in the pre- and posttests

Our findings indicate that students who studied in the TEAL format significantly improved their conceptual understanding of the various complex phenomena associated with electromagnetism. The average improvement (net gain) of both the Fall 2001 (28) and Spring 2003 (37) TEAL students from the pre-test to the post-test was significantly ($p<0.0001$) higher than that of the control group of Spring 2002 (16).

To analyze the effect of the TEAL classroom and learning materials on each academic level separately, we examined the relative improvement measure ⟨g⟩ for each level, which is defined as follows (Hake, 2002).

$$\langle g \rangle = \frac{\%Correct_{post-test} - \%Correct_{pre-test}}{100 - \%Correct_{pre-test}}$$

Table 1 shows the results of the two experimental groups and the control group. The relative improvement of both experimental groups was significantly ($p<0.0001$) higher than that of the 2002 control group.

Table 1. Relative improvement of conceptual understanding of Fall 2001 and Spring 2003 experimental vs. the Spring 2002 control group students

| Group | Experimental Fall 2001 | | Experimental Spring 2003 | | Control Spring 2002 | |
|---|---|---|---|---|---|---|
| | *N* | ⟨g⟩ | *N* | ⟨g⟩ | *N* | ⟨g⟩ |
| **Total** | **176** | **0.46±0.26** | **514** | **0.52±0.22** | **121** | **0.27±0.31** |
| High | 58 | 0.56±0.29 | 40 | 0.46±0.33 | 19 | 0.13±0.43 |
| Intermediate | 48 | 0.39±0.26 | 176 | 0.55±0.22 | 50 | 0.26±0.34 |
| Low | 70 | 0.43±0.22 | 298 | 0.51±0.19 | 52 | 0.33±0.20 |

The TEAL project was well received in the small-scale implementation. However, in the large-scale experiment students expressed both positive and negative attitudes in the course survey. Below are a few examples, both positive and negative.

- "The in-class discussions were particularly helpful because people had the opportunity to defend their opinion and try to convince others that they were right. In doing so, I picked up more practical explanations (without use of equations) to problems."
- "The 2D/3D simulations gave a real example to see what was going on...even with the forces and things that aren't visible (e-fields, b-fields, etc)."
- "The online study guide was the most useful part because we were expected to know the concepts before class in order to complete the online assignments."
- "Frankly, I don't think 8.02 [*the electromagnetism course*] TEAL should be forced on people. Lecture format is a LOT better for some people, for example me."
- "... You can't let the blind lead the blind, and I'm afraid that's exactly what teamwork in physics is...especially when we haven't learned the material individually first."

*Research Limitations, Summary and Discussion*

The research has a number of limitations, which stem from the fact that not all the variables of students in the two experimental groups and the control group were identical. Unlike the experimental group students, who responded to both conceptual and analytical problems as part of their weekly assignments, the control group students had to solve only analytical problems in their weekly assignments. The only times the control group students were presented with multiple choice conceptual questions were in the pre and the post tests. The conceptual pre and posttests administered to the two experimental group students were mandatory, whereas the control group students volunteered to take the pre- and posttests and were compensated for their time. Students in the experimental group were credited for attendance as well as for active participation in desktop experiments and visualizations. This element was not part of the control group scoring scheme. Consequently, experimental students' attendance was over 80% while that of control students was about 50%.

However, the experimental students consisted of the entire class population, while the volunteers in the control group accounted for about 20% of their class. The average final grade of the volunteers in the traditional course was higher (66 out of 100 points) than the average score of the rest of the class (59). Therefore, significant difference between the experimental and control groups might have been even more accentuated had we used a random sample of the control class.

Our study has established that the TEAL-studio format has had a significant and strong positive effect on the learning outcomes of MIT freshmen. The failure rate, a major triger for the project, has decreased sixfold while the relative improvement has almost doubled. The TEAL format incorporated into the classroom a collaborative, active learning approach, enhanced by visualizations, desktop experiments, web-based assignments, a personal response system, and conceptual questions. These teaching methods, applied within the TEAL framework, enhanced the students' ability to transfer concepts such as electromagnetic field lines and associated phenomena from the abstract level to the concrete one, thereby contributing to better conceptual understanding of these physical phenomena. The plan is to expand the implementation of the TEAL Project from large-scale electromagnetism course to mechanics as well.

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