Transforming Upper-Division Electricity and Magnetism

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Abstract. We transformed an upper-division electricity and magnetism course for physics and engineering majors using principles of active engagement and learning theory. The teaching practices and new curricular materials were guided by observations and interviews to identify common student difficulties. We established explicit learning goals for the course, created homeworks that addressed key aspects of those learning goals, offered interactive help room sessions, created and ran small-group tutorial sessions, and used interactive classroom techniques such as peer discussion and "clickers." We find that students in the transformed course exhibit improved performance over the traditional course, as assessed by common exam questions and a newly developed conceptual post-test. These results suggest that it is valuable to further investigate how physics is taught at the upper-division, and how PER may be applied in this context.

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INTRODUCTION

At most universities, including CU-Boulder, upper-division physics courses are taught using a traditional lecture approach that does not make use of many of the instructional techniques that have been found to improve student learning at the introductory level[1]. The CU Physics Department (supported by funding from the CU Science Education Initiative) chose to address this mismatch by transforming one of the core courses that defines what it means to learn physics as a major -- upper-division Electricity & Magnetism I (E&M I), typically taken in Fall of the Junior year. While considerable work has been done in PER on student understanding of E&M at the introductory level[2-4], and within other upper-division courses such as mechanics[5] and quantum mechanics[6], research on upper-division E&M is fairly limited [e.g., 7].

E&M I involves sophisticated problem-solving skills, including higher-level mathematical facility[8,9]. Courses in E&M typically focus on the formalism and theory of E&M through standard solution techniques and derivation of formulas, often at the expense of explicit treatment of phenomena and concepts. Our challenge was to adapt techniques used successfully at the introductory level (such as clickers and small group work) to this upper-division course. The transformed course is in the process of being taught for the second time, whereupon it will be taught by a non-PER faculty who previously served as co-instructor.

THE TRANSFORMATION PROCESS

The transformation efforts focused on helping students construct their own understanding through active engagement. We began the process of course transformation by consulting faculty who taught the course in past years, to increase likelihood of sustaining the transformations[10,11]. This project supported productive collaboration between two sets of generally non-overlapping instructors – those who tend to teach the introductory courses (using interactive techniques), and those who tend to teach the upper-division courses (using traditional methods).

Learning Goals

The content of the course is canonical for E&M I and there was strong consensus among faculty on what topics to cover: electro- and magneto-statics, including techniques for solving for the potential and fields in matter. This covered Chapters 1-6 of the text by D.J. Griffiths[12]. Beyond the *content* of the course, we collaborated with key faculty to develop a set of learning goals such as, "Students should be able to achieve physical insight through the mathematics of a problem," and "Students should be able to choose and apply the problem-solving technique appropriate to a particular problem, including use of approximations, symmetries, and integration."[13]

CUE Post-Assessment

Because traditional measures of assessment (e.g., homework and exams) often do not explicitly assess progress on many of these learning goals, we developed a junior-level conceptual post-course assessment tool: the Colorado Upper-division Electrostatics (CUE) assessment[13], to be fully described in a future publication. CUE questions were based on informal observations of students in problem-solving sessions, formal student interviews (which also served as instrument validation), and faculty discussions[14]. The final instrument is a 17-question test consisting of written explanations, conceptual reasoning, sketching, graphing, and a few multiple choice questions, intended to be completed in a single 50-minute lecture period.

What Changed?

In many ways the new course was not a dramatic departure from traditional courses. The primary classroom activity was interactive-style lecture, unlike other models that have switched completely to small group work[15-17]. However, many aspects of the course were carefully designed to fulfill the learning goals of the course, primarily through the methods of active engagement, making the physics explicit, and requiring students to articulate their reasoning. For example, student difficulties in understanding bound charge were tackled with conceptual clicker questions and sense-making of calculations on homework. We had the equivalent of 2 instructors: A single instructor could expect to run one 2-hour weekly help session, and a one-hour weekly tutorial session (see below) with the help of a good graduate Teaching Assistant.

Lecture Techniques & Clickers: Lectures typically involved high levels of student engagement through questioning, conversation, simulations, student work on small whiteboards and kinesthetic activities[13,14,18]. We used about 2-3 clicker questions in each 50-minute class. The questions were closely linked to the lecture, either expanding upon material that had just been covered or leading into the next topic. We observed high levels of conversation and argumentation before answers were submitted. The questions may have been, overall, too easy, as the mean percent of clicker questions answered correctly was quite high (87%).

Homework Assignments: Practicing solving physics problems may be one of the most powerful and certainly the most time-consuming contribution to student learning at this level. Drawing from multiple resources, we created a "bank" of homework questions[13], that we used to compile assignments. Assignments explicitly required students to connect abstract problems to real-world situations or physical contexts, articulate what they expected the answer to be, make sense of their answer, and draw on common physicists' tools such as approximations, expansions, and estimations. Many of these goals were achieved with minimal effort by adding a sense-making component to more traditional problems. Students indicated that they viewed these assignments as unusual but highly valuable learning experiences.

Weekly Help Sessions: We ran optional 2-hour group Socratic-style help sessions on the two evenings before homework assignments were due. Students worked in groups, with a large whiteboard on the table. The whiteboard served as a public space for discussion among students and between teacher and students. In this context, whiteboards are preferable to pen and paper because evidence of any mistake can easily be wiped away, thus encouraging students to try out new ideas. Attendance at these sessions was high, with an average of 65% of the class attending each week.

Tutorials: We created and implemented 10 weekly tutorials. These were designed to reinforce topics presented in lecture, expand on these topics, and prepare students for the upcoming homework. They were created in the general format of the University of Washington *Tutorials in Introductory Physics*[19], with which most students were familiar. The activities were often inspired by unpublished work by others[15-18]. The weekly tutorials were optional but typically attended by 50% of the class. Students worked in groups of 3-5 students, with a group whiteboard.

One possible use of such tutorials is to replace the applications and examples of a topic (typically performed by the professor in lecture) with a student-centered tutorial activity. For example, one could imagine that students benefited more from *doing* a separation of variables problem in tutorial than *watching* it done in lecture. Several tutorials also incorporated demonstrations, which were popular with students and were generally difficult to incorporate into the short lecture periods. These tutorials allowed students to familiarize themselves with new material by working actively, and allowed us to test activities to potentially replace some lecture in future semesters.

COURSE ASSESSMENT

We compared two recent implementations of the course – one Traditional (N=41) and one Transformed (N=21), to assess the impacts of the transformations. The low N in the Transformed course is due to the offsequence timing of the course relative to the typical course sequencing for majors.

Demographics & Course Information

The student populations in each course were similar in terms of gender ratio (24/27% female), ethnicity (73/81% white), and college (60% Arts & Sciences, 40% Engineering in both). Students entered each course with very similar backgrounds. They had similarly high predicted GPA (mean 3.2; based on a regression analysis of high-school performance), GPA in pre-requisite physics and math courses (mean 3.1).

The two instructors differed significantly in their approach and background. The Traditional course was taught by a theoretical physicist primarily using traditional lecture methods. He tends to teach upper-division courses, and has average overall instructor ratings (based on the standard university-wide course questionnaire) of 90% and 75% for upper- and lower-division courses, respectively (For comparison, departmental 7-year averages are 84% and 76%.) The instructor for the Transformed course and is a member of the PER group who tends to teach lower-division courses and has used interactive techniques in these courses for 9 years. His average instructor ratings are 97% and 94% for upper- and lower-division respectively. He was recently granted the university's highest teaching award, and many students mentioned the instructor as one of their favorite aspects of the course. We also note that this instructor has much less experience with E&M than the Traditional instructor.

Student grades were similar in both courses (mean 2.9-3.0), though those in the Transformed course were skewed slightly higher. Both instructors had a tendency to give a majority of grades in the A-B range. Similar portions of students failed each course (5-7%). Students in the Transformed course reported spending 11 hours per week on the course (with class time), whereas those in the Traditional course reported spending an average of 8 hours. Student comments on the Transformed course were extremely favorable, and that course received higher overall course ratings (92%) than the Traditional course (85%).

Attendance & Homework

Attendance was much higher in the Transformed course than the Traditional course – attendance in the Traditional course ranged from 65-85% (using attendance data gathered on two days). In the Transformed course it averaged over 90% (based on clicker data). This high attendance may have had a positive impact on student learning not directly attributable to pedagogical technique. Help sessions and tutorials did not have measurable impact on student performance, but are confounded by self-selection effects. Both sessions were mentioned by many students as very positive aspects of the course.

Homework scores were not correlated with any assessment measures except for the final exam ($r=0.37$, $p<0.05$). We found this lack of correlation to be surprising, given the high pedagogical value that faculty place on homework. The same lack of correlation was noted for clicker scores. We suggest that perhaps homework and clickers are important parts of the learning *process* but may not represent as useful measures of student *assessment.*

Traditional Assessments

Five exam problems were given in common between the two courses and graded on a common rubric. See Fig. 1 for results. The transformed course positively impacted student learning on these traditional problems: Students in the Transformed course performed better on all questions, a difference that was statistically significant for all questions except Q5.

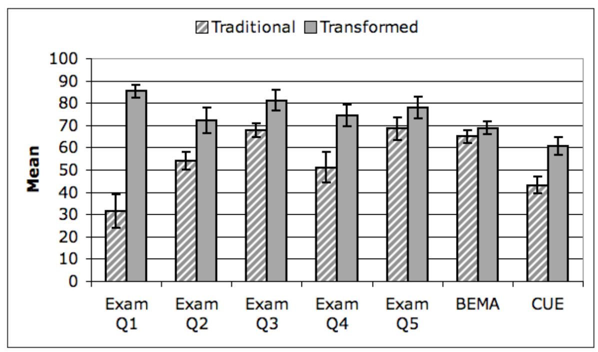

FIGURE 1. *Comparison of student performance. Error bars indicate the standard error of the mean. All differences are significant ($p<0.05$) except Q5 and BEMA. $N_{Trans}=21$ in for all Q's, N_{Trad} as follows**: *BEMA (N=33); CUE (N=26)*
Q1: *Conceptual Gauss' Law (N=7);*
Q2: *Direct integration – final (N=41);*
Q3: *Sep. of variables (N=39) ;* ***Q4***: *Ampere's Law (N=9);*
Q5: *Direct integration - midterm (N=39).*

Conceptual Assessments

Students were given two conceptual assessments: The Brief Electricity & Magnetism Assessment (BEMA[21]; end of term or next semester)** and the CUE (end of term).

* Only a subset of exams in this course were available for re-grading.
** BEMA scores have been observed to be stable over time in this course and other iterations of it[22].

BEMA: There were no statistically significant differences between BEMA scores for students in the Traditional (mean 64.9 ± 3.0) vs. Transformed (mean 68.8 ± 3.0) course. There is no strong evidence, therefore, that BEMA performance is significantly impacted by the transformed course. These results mirror those for non-transformed E&MI courses[22]. We note that many of the topics on the BEMA are not explicitly addressed in this junior-level course. Thus, this finding may indicate that student difficulties must be explicitly addressed in order for learning to occur.

CUE Assessment: Items on the CUE assessment were significantly correlated with the overall CUE score (typical $r=0.50$, $p<0.01$) on all questions except one, indicating good item discrimination. CUE scores were also positively correlated with overall course score ($r=0.53$, $p<0.001$).

Fourteen CUE questions were given in common in both semesters ($N_{Traditional} = 25$; $N_{Transformed} = 21$), and graded on a common rubric by two independent graders. Students in the Transformed course scored better on the CUE overall (61±4.0) than those in the Traditional course (43±3.7 $p<0.001$), a difference which remains even if the portions of the exam requiring explanations (which were not stressed in the Traditional course, and that many students in that course left blank) are removed. CUE scores were distributed in a roughly Gaussian curve, and were low relative to exam scores because the test was scored more strictly than had it been given as an exam. Students in the Transformed course scored at least 10 points higher on each individual question on the CUE, except three (although only 8 of these differences were statistically significant due to low N). This difference is roughly equivalent to a letter grade.

CONCLUSIONS

We have transformed an upper-division E&M course using principles of active engagement, and find improved student learning on both calculational and conceptual problems. Students were very enthusiastic about the course. Several indicated that they felt that homework assignments were very valuable learning tools and others noted that they felt that the instructor cared about their learning. Although we cannot rule out the possibility that increased contact hours with the material (through increased attendance and time spent per week) and increased motivation (related to instructor) resulted in improved learning rather than the specific course reforms, our results strongly suggest that pedagogical techniques that improve learning in introductory classes can have similar benefits in upper-division, resulting in improved learning for future physicists, teachers and engineers.

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