Longer term impacts of transformed courses on student conceptual understanding of E&M.

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Abstract. We have measured upper-division physics majors' performance using two research-based conceptual instruments in E&M, the BEMA [1] and the CUE (Colorado Upper Division Electrostatics assessment[2].) The BEMA has been given pre/post in freshman E&M (Physics II) courses, and the BEMA and CUE have been given pre/post in several upper-division E&M courses. Some of these data extend over 10 semesters. We used PER-based techniques to transform the introductory and upper-division courses starting in Fall 2004 and 2007, respectively [2,3]. Our longitudinal data allow us to measure "fade" on BEMA performance between freshman and junior year. We investigate the effects of curricula on students by comparing juniors who were enrolled in traditional vs. transformed physics as freshmen, as well as those who were enrolled in traditional or transformed upper-division E&M I, using both BEMA and CUE measures. We find that while freshman reforms significantly impact BEMA scores, junior-level reforms affect CUE but not BEMA outcomes.

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INTRODUCTION

At CU-Boulder, we have transformed our Calculus-based introductory physics sequence (Phys I and II) using research-based approaches[3]. In particular we have adopted U. Washington Tutorials in recitations[4,5] and peer instruction[6] in lectures. Short-term impacts in E&M have been measured by a variety of instruments, including the BEMA[1], and traditional exams[7]. Previously, we reported on long-term outcomes[8] by measuring physics majors' BEMA scores after completion of our upper division E&M courses (Phys 301 and/or 302). That longitudinal work can be summarized as follows: students who take our transformed introductory CU Physics II *with Tutorials* perform significantly better on the BEMA after upper-division physics than students who had taken our more traditional Physics II *without tutorials*, or who bypassed it completely. However, student BEMA scores after Phys 301 were comparable to scores after Phys II, suggesting that traditional upper-division courses may not significantly impact student BEMA performance.

For the last two years, we have engaged in research-based transformations of Phys 301[2], which typically covers the first half of Griffiths' text[9], electro- and magnetostatics. In parallel we developed a conceptual assessment tool, the CUE (Colorado upper-division E&M instrument)[10]. Here, we compare student performance on the CUE after four terms of Phys 301 as taught (a) traditionally, (b) by the new curriculum developer, (c) by a team of PER and non-PER faculty, and finally (d) by the non-PER faculty member on his own. Pre/post Phys 301 BEMA data provide another measure of the impact of our course transformations on student conceptual performance.

A synopsis of the current work is as follows[11]: we confirm earlier results showing that upper-division physics students, who took Tutorials as freshmen, score higher on the BEMA over time. We find that traditionally taught upper-division E&M courses have negligible impact on BEMA scores. We find a relatively small (but statistically significant) "fade" of BEMA performance over the ~1.5 year period between our transformed Physics II and the start of Phys 301, with a corresponding small rebound after traditional Phys 301, but no additional rebound after Phys 302. We see little difference in performance on different subtopics in E&M when questions are grouped categorically. We find direct evidence that our transformed Physics 301 course significantly improves CUE scores as compared to traditional instruction, but only modestly impacts BEMA scores.

LONGITUDINAL IMPACTS OF THE FRESHMAN E&M EXPERIENCE

We collected pre-post BEMA data for CU's Physics II for ten terms. The pre-test average is very stable at 26±1%. Post-scores vary somewhat with instructor, ranging at CU from 50-61% (average 55%, σ=16% for N=2626 students). As indicated by data from peer institutions[12] BEMA post-test scores in traditionally taught classes typically range from 35-45%, about 15 points lower than our (transformed) courses. In Fall 2004 our Physics II course was transformed by the introduction of UW Tutorials. We label this transformed freshman course as "with Tutorials", since this was the single significant and consistent change which occurred. Narrowing our data set down to the roughly 200 students who later took upper division Physics at CU, the average Phys II BEMA pre- and post-test score was 33±2% and 68±2% respectively: our future physics majors are close to a standard deviation above our overall post-Phys II BEMA averages. For the purposes of this longitudinal comparison, we average Physics 301 and 302 BEMA data when available for any given student, and exclude students who never took Physics II at CU.

Table 1 summarizes average BEMA scores after upper division physics for two populations of students - those who did or did not take freshman Tutorials. The difference between these populations is statistically and pedagogically significant; students who went through our transformed introductory class score on average ~17 points higher on the BEMA after upper division physics (a 2-tailed t-test yields $p<<.01$). We have no direct measurement of how non-Tutorial students would have scored on the BEMA directly following Physics II, because we only began administering the BEMA after transforming the freshman course.

TABLE 1. Upper division BEMA scores collected over 7 earlier terms of upper division data, *post*-301 or 302.

CU Freshman experience	BEMA score	St. Dev.	N (# students)
No Tutorial	54%	20%	72
Tutorial	71%	15%	67
(All, combined)	62%	20%	139

IMPACTS OF TRADITIONAL UPPER DIVISION E&M

Our data do not indicate that post-301 or 302 BEMA scores depend on the *upper*-division instructor; when investigating the BEMA scores for students who have *not* taken freshman Tutorials (via ANOVA) we find no significant difference between courses ($p>>.05$). In addition, average BEMA post-test scores after Phys 301 or 302 are not significantly different from average post-test scores after Phys II. To examine this more directly, our longitudinal data set allows us to track 37 individual students from freshman through upper division E&M. These students gained an average of 39±2 points during the course of Physics II (with Tutorials), but gained an average of only 0±2 points from the end of Physics II to the end of Phys 301. A slightly different set (N=41) of students took the BEMA after both Phys 301 and 302; the average shift from the end of 301 to the end of 302 for these students was also 0±2. Thus, although our transformed *introductory* pedagogy appears to make a large difference on upper division physics students' performance on the BEMA, neither of our traditional *advanced* E&M courses appears to directly impact the BEMA score.

IMPACTS OF TRANSFORMED UPPER DIVISION E&M I

Starting in Spring 2008, we implemented research-based changes[2] in the curriculum of Phys 301, including concept tests, whiteboard and kinesthetic activities in class, and modified homeworks to increasingly emphasize sense-making, explanation, and real-world connections. To assess the impacts of these changes, we have used two very different conceptual instruments: the BEMA and the CUE.

BEMA measures

Table 2 summarizes BEMA scores in four recent terms of Phys 301, including the average shift from post-Phys II to post-Phys 301 (N is smaller because not all students took Phys II with Tutorials, and of those who did, some missed the post-test)

TABLE 2. Upper division BEMA scores collected after Phys 301 in recent terms. Term A was traditionally taught, B-D all used our transformed curriculum.

Faculty background (N students in class)	BEMA score	Shift from post Phys II
	66±3% (N=31)	0±3% (N=19)
B: Curric. developer (PER) (N=21)	72±2% (N=20)	+5±2% (N=14)
C: PER & non-PER team-teaching (N=51)	67±2% (N=42)	+8±2% (N=31)
D: Non-PER (from previous term) (N=36)	61±2% (N=21)	-6±5% (N=7)

BEMA post-test scores after our transformed 301 course taught by PER faculty (semesters B and C) are at best marginally higher than the averages from

earlier traditional terms of 301 (Table I), and are not significantly higher than the most recent traditional course (semester A). The *shift* in BEMA score from post-Physics II to post-Phys 301 is positive (and statistically different from zero) for the first two transformed terms (B and C), but the non-PER taught term (D) is not significantly different from the usual "no shift" result. It appears that our upper division course transformations have, at best, only a small positive impact on student conceptual understanding as assessed by the BEMA. It remains to be seen whether students in courses taught by non-PER faculty can also see this benefit.

Comparing post-Physics II to post-Phys 301 scores leaves open the issue of separating the natural decline after Physics II from subsequent gains as a result of Physics 301. To help assess this, we implemented a BEMA *pre*-test on the first homework set of the Phys 301 course for the most recent two semesters. The results for these two terms (only) are shown in Figure 1. There is a ~5% "fade" from Post-Phys II to *Pre*-Phys 301, with a rebound after 301. Educational psychology literature[13] indicates a fade of this magnitude is quite small for a time span of ~3-4 semesters, but note that our population of students is very select; these are physics majors, exposed during the intervening time to concepts potentially related to E&M in several lab and mid-level physics courses.

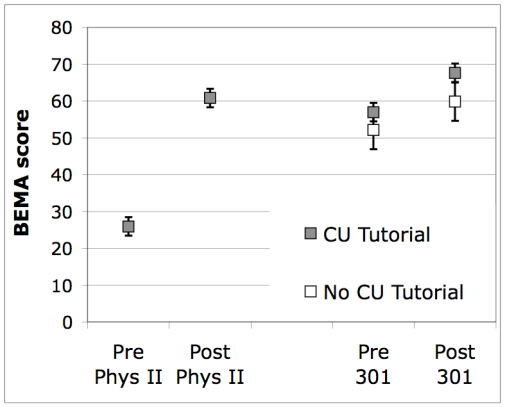

FIGURE 1. Evolution of BEMA scores over time, for future physics majors. The students shown are N=38 individuals who we were able to track longitudinally from Physics II through our most recent two semesters of transformed Phys 301. Hollow squares show N=19 students who skipped Physics II (and thus never had Tutorials)

BEMA sub-topics

Does the fade and rebound in performance seen above on the BEMA arise from particular areas of content? To examine this, we chose clusters (3-8 questions per category) of BEMA questions, based on broad topical categories as determined (post-hoc) by the authors. In Figure 2, we trace the time development of student performance on our 6 chosen subsets of questions over time, from post-Physics II (white), to pre-Physics 301 (light grey), to post-Physics 301 (dark grey). (We have averaged over the two most recent semesters)

Fig 2 shows a similar pattern to the overall picture in Fig 1: students' performance fades only slightly over the long time span from end of freshman to start of upper-division, and then rebounds after the upper division semester. The fade is not statistically significant in any category except "circuits". The rebound is significant in each category except circuits and Faraday's law. (Circuits are not covered in any way in our Phys 301 course, and Faraday's law is treated only very briefly at the end of the course, this topic is where our Phys 302 class starts.) The largest gain is in the magnetostatics category, a topic emphasized heavily in the second half of Phys 301.

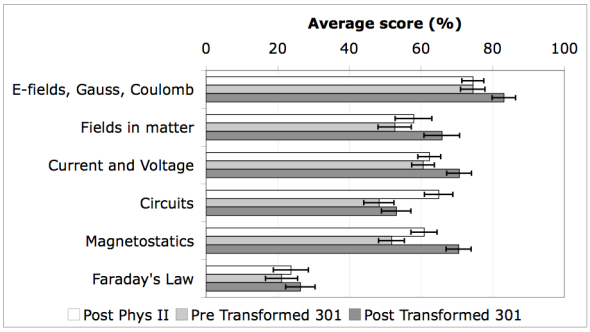

FIGURE 2. Comparison of performance on subsets of BEMA problems, for a matched group (N=38) of students with post Physics II (white), Pre (transformed) Phys 301 (light grey), and Post (transformed) Phys 301 scores (grey).

CUE measures

Starting in Fall 2007, we began efforts to assess student learning in Phys 301 based on faculty consensus learning goals, and observations and interviews of students, which led to the CUE assessment tool.[2,10] The CUE is a challenging, high-level assessment targeted explicitly at junior-level content. CUE scores correlate well with our other measures of student performance - the Pearson correlation coefficient of individual's CUE scores to their BEMA post scores is r=0.54, and the correlation of CUE to course grade is r=0.49, indicating that the CUE taps into skills required for good performance on other (conceptual and traditional) measures of learning. The instrument is still evolving, but we present in Table 3 preliminary results comparing the three transformed terms and one earlier term (term A

in Table 2), a traditional Phys 301 class. The middle column shows pre-CUE scores (a subset of the CUE designed to be accessible to students before taking Phys 301. The final column shows results for common CUE exam questions across the evolving versions of the instrument[10], to allow a more direct comparison.

TABLE 3. Upper division CUE scores, before and after Phys 301 in recent terms. Term A was traditionally taught, B-D all used our transformed curriculum.

Faculty background	CUE pretest	CUE post-test (common questions only)
A. Traditional course, non-PER faculty	NA	42±3% (N=26)
B. Curriculum developer (PER)	NA	64.5±4% (N=21)
C. PER & non-PER team teaching	33±4%	57±3% (N=48)
D. Non-PER faculty (from previous term)	33±5%	63±3% (N=27)

There is no significant difference among the three transformed classes (an ANOVA test of CUE post-test across semesters B-D yields p=0.42) but the *average* CUE score of these transformed classes is significantly higher than the traditional course ($p<<.01$). Overall, CUE results from Table 3 indicate that our Phys 301 course transformations have a significant effect on conceptual understanding at the upper-division level. The impact of our transformed pedagogy stands out more strongly as measured by the CUE (Table 3) than by the freshman-level BEMA (Table 2). CUE pretest scores are low (similar to BEMA pretest scores at the start of Physics II), and we see consistent and significant improvement, and higher final CUE scores, in all three terms of transformed pedagogy, compared to the semester taught traditionally.

SUMMARY AND CONCLUSIONS

We are interested in both short- and long-term impacts of research-based transformations at both the lower- and upper-division in physics classes at CU. Our collection of BEMA data in transformed introductory physics, traditional and transformed upper-division and CUE data in transformed upper-division Phys 301, allows us to systematically investigate questions of longer term learning gains. Broadly, we have seen lasting positive impact of the introductory level reforms on future physics majors. Elsewhere [2,8,11], we have seen that this improvement comes at no cost in terms of traditional upper-division measures. We find that traditional upper-division courses have no measurable impact on BEMA scores, while transformed upper-division courses have at best a small positive effect. However, transformed class structure has a large positive impact on upper-division student understanding as measured by the CUE. This data tells a story of the targeted nature of transformations – engaging students interactively with material creates change that is remarkably robust over time. However, interactive techniques aimed at a higher level does not automatically translate to an improved foundational understanding, despite improved performance at the higher level. This is a finding that goes counter to the assumptions of many faculty – underlying conceptual understanding is not "fixed" by an improved grasp of the material at a higher technical level.

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