

PHYSICS EDUCATION RESEARCH SECTION

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Thinking like a physicist: A multi-semester case study of junior-level electricity and magnetism

Stephanie V. Chasteen and Steven J. Pollock

Science Education Initiative, University of Colorado, Boulder, Colorado 80309 and Department of Physics, University of Colorado, Boulder, Colorado 80309

Rachel E. Pepper

Department of Integrative Biology and Department of Civil and Environmental Engineering, University of California, Berkeley, California 94720

Katherine K. Perkins

Science Education Initiative, University of Colorado, Boulder, Colorado 80309 and Department of Physics, University of Colorado, Boulder, Colorado 80309

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Physics faculty agree on many of the skills and habits of mind they expect physics students to acquire by the end of their degree, including mathematical sophistication, problem-solving expertise, and an ability to work independently and become expert learners. What is less clear is how these outcomes are best achieved within the context of upper-division courses. Focusing on one key course in the career of an undergraduate major—junior-level Electricity & Magnetism (E&M)—we have investigated this critical question over the course of 4 years and across multiple universities and instructors. With the aim of educating our majors based on a more complete understanding of the cognitive and conceptual challenges of upper-division courses, we transformed junior-level E&M using results and theory from education research. We present the process and content of the transformation and several measures of its success. Students and instructors enjoyed the new course materials. Students in courses using the new materials outperformed those in traditional lecture-based courses on a conceptual assessment and on some aspects of problem-solving, though not calculational skill. These results suggest that using student-centered methods at the upper-division can improve outcomes for many students. © 2012 American Association of Physics Teachers. [<http://dx.doi.org/10.1119/1.4732528>]

I. INTRODUCTION

Upper-division physics courses tend to be 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 (such as small group work, personal response systems, or tutorials).^{1,2} Our department chose to address this mismatch by developing resources for one of the core courses that defines what it means to learn physics as a major: upper-division Electricity & Magnetism I (E&M I). While physics education researchers have examined the teaching of E&M at the introductory level in some detail,^{3,4} research on upper-division E&M is still fairly limited,⁴⁻⁶ and documentation of experimental course approaches are rare.⁷

Many faculty hope that experience with sophisticated mathematical tools (such as vector calculus) in E&M may lead students to a deeper understanding of fundamental topics such as Gauss' Law, current, or voltage. However, in studying other upper-division courses (primarily classical

mechanics, thermodynamics, and quantum mechanics),^{8,9} researchers have started to document what many instructors have suspected: students' conceptual difficulties remain long after they have moved on from introductory courses, presenting a hurdle to students' deeper understandings of such topics. Additionally, combining mathematical skill with physical insight is a non-trivial task. As suggested by Redish,¹⁰ "Math may be the language of science, but math-in-physics is a distinct dialect of that language. Physicists tend to blend conceptual physics with mathematical symbolism in a way that profoundly affects the way that equations are used and interpreted." In other words, it's not enough to be mathematically skilled; students must learn to use mathematical tools to gain insight into physical phenomena through ever-increasing fluency with the language and problem-solving approaches of physics. Traditionally, these complex skills are assumed to "come along for the ride," as students work on difficult homework sets and labs. But many faculty members have expressed dissatisfaction with the results of this approach. The successful application of

research-based techniques in introductory physics suggests that these techniques might also be used to improve learning at the junior level.

We have thus applied interactive techniques to the junior-level E&M course, with an increased focus on phenomena and concepts. Our course transformation efforts were driven, primarily, by the desire to better prepare our upper-division physics students for the skills expected of them by faculty: increased mathematical sophistication, the development of problem-solving expertise, and a mature approach to learning and to solving complex problems. We adapted pedagogical techniques used successfully at the lower division, such as Peer Instruction and tutorials. The transformed course has been taught five times at the University of Colorado,¹¹ and our materials have been used in courses in at least three external institutions.

In this paper, we present our methods and results in the hopes that it will prove useful to other instructors and departments. As we will show, we found that students enjoyed the transformed courses and the changes improved student learning. However, there is still much to explore as teachers and researchers in this area. A companion publication¹² reports on more details of this study.

II. “THINKING LIKE A PHYSICIST”

We focused our transformation efforts on the first semester of a two-semester junior-level sequence in electromagnetism (hereby referred to as PHYS301). This course covers electro- and magneto-statics in vacuum and in matter (Chaps. 1–6 of the text by Griffiths¹³) and is typically taken in the fall of the junior year. Pre-requisites for PHYS301 are the three-semester introductory physics sequence, and the combined mechanics/math-methods course. Typically, 30–50 students enroll in a given semester of PHYS301.

In order to determine what we were trying to “fix” with our course transformations, we convened a working group of faculty¹⁴ to discuss the learning goals of PHYS301: what should students be able to do at the end of the course? The resulting learning goals are available as supplementary material¹⁵ and on our website¹⁶ and address the overarching goals of mathematical sophistication, problem-solving expertise, and developing as a physicist. For example, “Students should be able to translate a physical description to a mathematical equation.” These course goals helped us to operationally define what this course is about and what “thinking like a physicist” meant in the context of a junior-level physics student. In order to tap into student opinions on the course material, we surveyed 369 alumni to determine how PHYS301 had served their needs after graduation.

PHYS301 is seen by many as an important point in a physics students’ career—students are expected to develop the mathematical sophistication and problem-solving expertise necessary to solve increasingly complex problems and to learn to see meaning behind the mathematics. Our alumni also see this as a milestone in terms of their identity as physics students: 73% indicated that they had “matured as a physicist or a student” in this course: “I learned to sit back and examine a problem before diving into the math,” and “This was the first really challenging physics course I took and it gave me a better understanding of what physics was really all about.”

Faculty in the working group indicated that they expect this improved responsibility on the part of students.

This course also represents one of the first opportunities for students to apply newly acquired mathematical tools to physical situations: “This was one of the first times that

material I had previously learned came back in a much more mathematically rigorous way, and I saw how you can add depth to a problem,” said one graduate.

From the comments of the alumni and the learning goals developed by faculty, we can identify three central ideas that form the fabric of the course:

1. Mathematical sophistication:
 - *Translating physics to mathematics* (e.g., setting up a problem, including visualization of the problem and its parameters);
 - *Conceptual and physical understanding of mathematics* (e.g., making sense of equations and problem solutions);
2. Problem-solving expertise:
 - *Use of expert problem-solving tools* (e.g., approximations and checking limits);
 - *Expert problem analysis* (e.g., recognizing key parameters and combining knowledge from multiple sources to devise and execute a strategy);
3. Developing as a physicist:
 - *Independence and discipline* (e.g., taking responsibility for learning, and working hard);
 - *Metacognition* (e.g., reflecting on one’s own learning and learning how to learn);
 - *Expert-like approaches to problems* (e.g., planning an approach, having the confidence to see a problem through to the end, and checking one’s work);
 - *Ability to articulate one’s reasoning* (e.g., explaining one’s approach and method of solving a problem).

The transformed course was designed to address these core themes, which reflect comments by alumni and the learning goals developed by faculty.

III. THE COURSE APPROACH

In addition to the faculty working group and alumni survey described above, we also reviewed the literature, observed classes and help sessions, and interviewed numerous students enrolled in the course. These formative assessment measures informed material development and the course approach. Student interviews and observations—as well as interviews with instructors using our course materials—continued over the 4-year duration of the project and informed continued material development and refinement. This course transformation model^{17,18} was developed by the Science Education Initiative (SEI) (Ref. 19) and has been used in other courses at CU and our sister institution at the University of British Columbia. Complete details on our methodology can be found in a companion publication.¹²

The pedagogical approach used for the new course was also informed by our previous experience with interactive engagement in large-lecture introductory courses and incorporated a variety of interactive and research-based techniques and pedagogical materials. Unlike other models that have switched completely to small group work,⁷ our course approach is mostly traditional with small interactive elements interspersed with standard lecture.

Instructional techniques used and/or materials developed for the course are described below. All course materials are archived online and freely available.²⁰

- *Student difficulties*: A detailed list of observed student difficulties with conceptual content and mathematical techniques was compiled, organized by chapter and topic.

- *Explicit learning goals*, as developed by faculty working group.
- *Lectures* were mostly traditional but included a variety of interactive elements, including clickers, spontaneous questioning, simulations, and student work on small whiteboards.
- *Clicker questions with Peer Instruction*.²¹ We used Peer Instruction, in which students are posed a challenging conceptual question, discuss with their neighbors for a few minutes, and vote on their answer choice using clickers. Then, the class as a whole discusses the question. About two to four clicker questions were used in each 50-min period and were crafted to help students make meaning of mathematics, to expand upon material that had just been covered or lead into the next topic.
- *Homework assignments* were redesigned and 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 (e.g., sketch, plot, estimate, etc.) to more traditional problems.
- *Optional help sessions* (typically replacing standard office hours) were offered twice a week for 1–2 h, in which students worked in groups on the homework assignment.
- *Optional weekly tutorials* were developed and refined over 2 years and include online tutorial pre-tests. In the tutorials, students worked in groups of three to five to complete a conceptually focused worksheet on the material. Tutorials were designed to reinforce topics presented in lecture, expand on these topics, and prepare students for the upcoming homework. Student attendance was optional but acceptably high (~40% of the class).

The fidelity of the course implementation varied by instructor, and there is some evidence that the more faithfully instructors attended to common student ideas and used interactive techniques, the higher the student satisfaction and learning.¹¹

IV. RESULTS

In order to determine whether, and in what ways, the course transformations were successful, we examined a variety of student outcomes, including conceptual learning, traditional exams, and student attitudes. We investigated these outcomes for upper-division E&M students over seven semesters at the University of Colorado. Five semesters used the research-based approach (CU PER-A through PER-E); the sequence of these courses has been randomized, i.e., PER-A was not necessarily the first semester of the transformation. Our point of comparison for the effectiveness of course transformations were two courses taught using a “standard” lecture-based instruction (STND-A and STND-B). Full details on the courses studied and the results are available in Ref. 12.

As described in detail below, we find that the transformations improved conceptual learning but did not impact student scores on traditional exams. Students who attended tutorials demonstrated higher levels of conceptual learning than those who did not. We also find that students and instructors enjoyed and appreciated the transformed elements of the course. These results cannot be easily explained by

pre-existing student characteristics—the students in these different courses were similar on many measures of preparation, such as cumulative GPA (3.1–3.2), GPA in physics courses (2.9–3.2), and pre-requisite courses. Students also completed the Basic Electricity and Magnetism Assessment (BEMA),²² which measures conceptual understanding of introductory-level topics in E&M. Student BEMA scores were similar across courses (58–61%, with the exception of PER-C and PER-E with BEMA scores of 69% and 55%, respectively).

A. Conceptual learning—the Colorado Upper-Division Electrostatics (CUE) assessment

Students in the transformed courses perform consistently better on a conceptual assessment developed to assess non-calculational aspects of the learning goals.

Only some of the learning goals identified by faculty are tested by traditional exams. Thus, a conceptual diagnostic—the Colorado Upper-Division Electrostatics (CUE) Assessment²³—was developed to assess students' conceptual understanding and to provide an independent measure of student achievement of the learning goals. The CUE is a 17-question open-ended conceptual test and includes an optional pre-test made up from those questions that a student entering PHYS301 could be reasonably expected to answer. More details on the CUE development and validation are available in Ref. 23.

The CUE was administered as a post-test at the end of the semester (before the final exam) to upper-division E&M students for seven semesters at the University of Colorado. To provide a more robust comparison, we also administered the CUE in nine courses at seven external institutions: three courses used our materials and six courses did not. Thus, in total, we present data for 466 students in order to assess the impact of research-based course transformations on student learning (Fig. 1). Courses are described more fully in Ref. 12.

Students in the transformed courses score higher on the CUE post-test than courses using standard lecture format. These results hold for courses at CU-Boulder and elsewhere. Taking each student as a data point, the average CUE score is higher in PER courses ($57 \pm 1.3\%$) than in STND courses ($44 \pm 1.6\%$ $p < 0.001$). Taking each course as a data point, the same result holds ($61 \pm 4\%$ PER vs $41 \pm 4\%$ STND, $p < 0.001$). If the CUE were a graded exam, this would be comparable to a gain of two letter grades. These results also held across students of different performance levels—course transformations appear to have positively affected both the top and the bottom tier of the student body, as defined by students' final grades in the course.

We can calculate student learning-gains by subtracting pre-test from post-test scores. Gains are useful because they allow us to compare students with different backgrounds. Gains on the CUE are similar across PER courses (about $30 \pm 2.5\%$), representing a rough doubling of the score from pre-test to post-test. By comparison, the estimated gains for STND-A and STND-B were only 7% and 14%, respectively.

Overall, these results suggest that the interactive techniques are consistently successful in improving students' facility with the concepts and problem-solving methods of junior E&M over five semesters at CU and at three external institutions. As the CUE was developed based on the learning goals developed by CU faculty, this suggests that we achieved

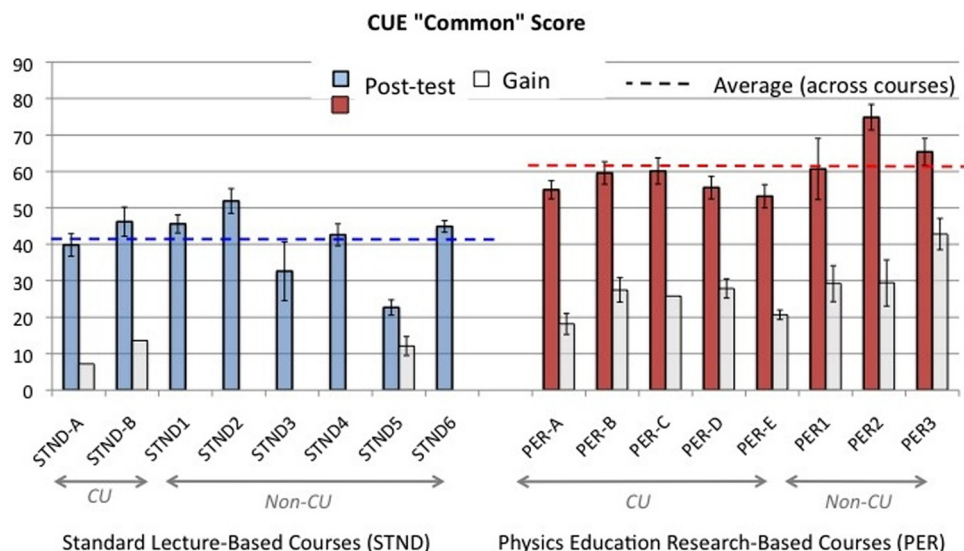


Fig. 1. CUE scores across institutions for $N = 488$ students. “Post-test” represents course average score (% correct) for the subset of CUE questions given in common across all exams (88 out of 118 possible points). “Gain” represents the course average for the difference between the pre-test and the subset of the post-test that matches the pre-test. Due to the lack of pre-tests for PER-C and STND-A and STND-B, pre-test scores are estimated based on the stable pre-test scores (33%) for other semesters of PHYS301 at CU. Error bars represent one standard error of the mean.

some measure of success in our aim of supporting the cognitive skills of developing physicists that are valued among physicists. Examination of the demographics of individual courses shows that these results cannot be easily explained by factors related to the students or instructors, such as incoming GPA, incoming score on the introductory conceptual assessment (BEMA), or instructor experience. Indeed, some of the highest scores on the CUE occur in classes where the instructor had no prior experience teaching the course. The robustness of these results over time, across instructors, and across institution also suggests that the course transformation effects can be sustained from instructor to instructor and across institutions.¹¹

B. Midterm and final exams

Student performance on traditional exam problems is not significantly affected by the course transformations, but students in transformed courses do engage in some expert problem-solving strategies more so than their traditional counterparts.

Since the transformed courses shifted the focus somewhat toward conceptual understanding, we also wanted to examine whether students in the transformed courses retained their calculational skills (e.g., integration and vector calculus) compared to students in traditional courses. Thus, we gave several exam questions in common between a standard course (STND-A) and two semesters of the transformed course (PER-C and PER-D). These questions (except Q1, see below) focused on abstract calculation and were graded by a single grader using a common, detailed rubric; however, scores were not validated through inter-rater reliability. Thus, these scores are shown for general comparative purposes only.

Five questions were given in common to students in the three courses (with the exception of Q4, not given to STND, and Q5, not given to PER-D). The wording below does not represent the phrasing on the actual exam; questions are paraphrased in the interest of brevity:

Q1: Gauss’ Law. Is Gauss’s Law true/useful for the case of a uniformly charged cube?

Q2: Dielectric cylinder. Given a dielectric cylinder with a frozen-in polarization, calculate the bound charge and potential. How should the potential drop off for large distances? Show that your potential matches your expectation.

Q3: Separation of variables. Find the potential everywhere for a non-conducting spherical shell with a given frozen-in potential that depends on $\cos^2(\theta)$.

Q4: Direct integration of disk. Given a flat uniform disk with a given surface charge that depends on φ , calculate the total charge and the voltage on the z -axis.

Q5: B of a cylindrical wire. Given the volume current density for a long wire (with a dependence on s), calculate B inside and outside the wire.

Results are shown in Fig. 2. Student scores on individual questions [Fig. 2(a)] were higher in PER-C compared to the STND-A course, but these results did not hold for PER-D, perhaps the result of differences in instructor experience or approach, or incoming student preparation. However, the course transformations did not have a statistically significant negative effect on the development of students’ skills in these types of calculations—a concern that had been voiced by some faculty in response to the increased focus on conceptual understanding in the new course and additional time spent on clicker questions at the expense of worked examples in lecture.

Upon closer examination of these exam results, however, we see evidence that the course transformation did appear to impact expert-like problem solving strategies and concepts. Questions were scored for correctness, and sub-parts were scored for (a) students’ ability to articulate their reasoning about an answer and (b) discuss limiting behavior where appropriate. Figure 2(b) shows that while students in all courses performed similarly on the calculational aspect of problems, the students in the two PER-based courses outperformed those in STND-B in their articulation of their reasoning and description of limiting behavior—aspects of expert-like problem-solving strategies that are valued by faculty as judged by the course learning goals.

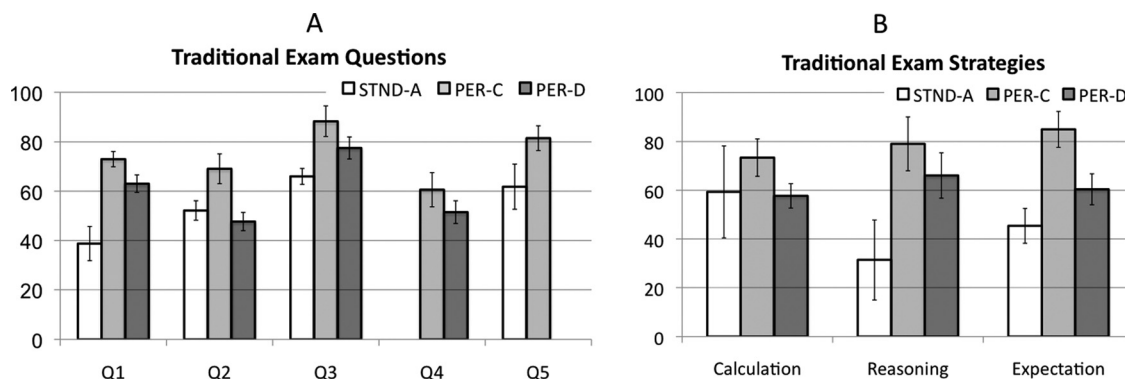


Fig. 2. Traditional exam results. Part A (Questions): Average percent score on five traditional exam questions across three semesters. Error bars represent one standard error of the mean. Part B (Strategies): Portions of questions grouped by problem-solving strategy: calculation and correctness (Q1 correctness; Q2 calculation of bound charge, V , and limiting behavior; Q3 calculation of V), reasoning (Q2 explanations, Q3 reasoning), and expectation of limiting behavior (Q2 articulation of limiting behavior). Standard error of the mean (SE) for categories in Graph B is obtained by adding the SEs for the individual questions in that category, in quadrature.

C. Student attitudes

We find, on a variety of measures, that students are positive about the course transformations at CU and see most of the course elements as useful for their learning. Results from all five semesters of the transformed course are given below.

Students completed opinion surveys at the end of PHYS301 to determine their opinions about the course: what they liked, what they didn't like, and what they found effective for their learning. Students were generally positive about the transformed courses and felt that the course elements were well connected. Several questions probed student confidence and interest in the course. See Ref. 15 for the complete results of student attitude data.

Across several different questions, students in PER-A demonstrated attitudes toward the course that were statistically significantly more negative than other courses on many questions: commentary from students and instructor suggested that (a) students did not completely buy-in to the course approach and (b) the instructor may not have been fully attentive to student difficulties at the junior level. The implications for sustainability of course innovations are discussed in more detail in Ref. 11.

We asked for student feedback on different elements of the course approach. All course elements were rated as useful or very useful for their learning, with the exception of whiteboards for in-class calculations (discontinued in later semesters). A typical response: "I especially liked the tutorials, clicker questions, and help sessions – I wish every physics class was run like this one." Students see clicker questions as extremely valuable,²⁴ e.g., "they give me a chance to talk over any questions I have with my classmates and work through the problem." Students also rated the tutorials highly in terms of the overall experience, effectiveness in encouraging interest in E&M, the intellectual challenge, amount learned, and overall enjoyment. Many students also gave spontaneous comments regarding the tutorials: "I really liked the Friday tutorials. They were (generally) fun, interesting, and a good jump-start to keep me excited over the weekend. Also, I learned a lot." Attendance was fairly high for an optional Friday activity: about 40% of the class, on average.

Out of all course elements, homework assignments and help sessions were mentioned the least by students when

giving spontaneous commentary about the course. However, given that homework is typically considered rather onerous, the student praise for this aspect of the course was satisfying. Students indicated that the challenge of the homework assignments was beneficial to their learning: "[The homework assignments] were challenging enough that you would feel like you actually learned/accomplished something once you finished a problem" writes one student; "Homeworks... were challenging, but very helpful to my learning," writes another. Several students in the transformed courses also mentioned that they appreciated the emphasis on conceptual understanding and/or an understanding of the physical world. The most common complaint was that the homework assignments were too long or hard: "I don't think the homework need be quite so bone-crushing... I think I was more worried about getting answers down than actually concentrating on the physics."

Student comments regarding homework help sessions suggest that they find it valuable to have this additional opportunity to interact with the instructor and found this more useful than one-on-one office hours or an instructor or TA presenting material to the group as a whole. Of particular interest to us was the number of student comments regarding how these sessions (and the difficulty of the homework in general) spurred both (a) communication and collaboration between students and (b) students own sense of what it meant to do physics. "[The homework help sessions] honed my skill of learning to ask the right question," said one student. Thus, the homework help sessions may be important opportunities for students to learn to "talk physics," with one another, and to receive instructor guidance and feedback as they learn to become expert problem-solvers.

Student positive attitudes toward the course are also reflected in the fact that students spend more time on the transformed course. End-of-term course evaluations ask students how many hours they spend on a course per week, including class time. Students in the PER courses consistently reported spending more time on the course per week than those in the STND courses in the study ("10–12 h" versus "7–9 h"). That is, with regard to the distribution of reported times, a larger fraction of students in the PER courses reported spending more time on the course than their STND course colleagues. The difference in reported times is significant; the average time reported by PER students is

more than one standard deviation higher than the average reported across the department as a whole. Using attendance on the day that course evaluations were administered, we find that attendance improved slightly in the PER courses (75%) compared to attendance in the three previous years of traditional courses (69%). Restricting scope to the seven courses in the study, attendance on the day that the CUE was administered was higher in PER courses (82%) than in STND courses (59%). However, a contingency table analysis of attendance rates on the 2 days reported above did not detect any association between attendance and course type. The trends reported appear to favor the PER courses, but additional data are needed to detect any significant differences. Together, these results suggest that it is reasonable to conclude that potentially improved attendance, extra out-of-class sessions, as well as additional reported time on homework, resulted in greater time on task for students in the transformed course.

D. Impacts of different course elements

While students liked all aspects of the course, it would be particularly helpful for an instructor to know which course elements are most important for maximum student learning. While we cannot completely answer this question, below we discuss the impact of individual aspects of this multi-faceted course transformation using results of a multiple regression analysis.

Did lecture attendance affect student learning? A major course transformation was the addition of clicker questions with peer instruction, and the course transformations have been shown to have a positive impact on student learning. So, in this way, lecture attendance does affect student learning. On the other hand, lecture attendance is only moderately correlated with CUE scores (Pearson's $r = 0.12$), and this appears to be mostly due to a self-selection effect: lecture attendance did not significantly predict student score on the CUE or course exams when students grades in prior physics courses were taken into account. Student lecture attendance may simply not vary enough for us to find an effect of this variable. Thus, we have only indirect evidence of the effectiveness of lecture and clicker questions for student learning.

We were able to demonstrate that attendance at tutorials has a positive effect on students' conceptual understanding of the material. Since tutorials are optional, we used multiple-regression to take into account self-selection effects by removing the effect of student background variables. Even when students' grades in prior physics courses were taken into account, students who attended more tutorials had higher CUE scores. Traditional exam scores, however, were not affected by tutorial attendance—these exam scores were best predicted by students' grades in prior courses. Details on this analysis are given elsewhere.^{12,25}

Lastly, we examined the impact of homework and homework help sessions. On average,²⁶ most students (86%) attended at least one homework help session but attendance varied quite widely; the homework help sessions are likely attended by the more diligent or motivated students in the course (as judged by the grades of the attending students.) Nonetheless, in a multiple-regression analysis, we find that attendance at homework help sessions is a significant predictor of homework score. Details on all multiple regressions are given in Refs. 12 and 24.

V. DISCUSSION AND CONCLUSIONS

We have researched and developed a course approach based on documented student difficulties and interactive instructional techniques to address the learning goals that our faculty have identified for junior-level physics students: mathematical sophistication, problem-solving expertise, and developing as a physicist. Course techniques included clicker questions, tutorials, homework, and homework help sessions, and instructors were provided with documented student difficulties. In this case study of a first-pass effort, we have presented evidence of overall student improvement on these goals based on the conceptual CUE exam, traditional course exams, student and instructor interviews, and attitude surveys.

Overall, students like the transformed courses, attend more often, and comment favorably upon all elements. Student conceptual understanding is significantly improved over traditional instruction, and these results hold across multiple institutions and instructors. On traditional exams, students' calculational abilities are not affected (positively or negatively), but students are more likely to provide good reasoning and demonstrate expert-like problem-solving skills on traditional exams. Tutorials are found to have a positive impact on student performance on conceptual exams, though not on traditional midterms and finals. Student comments suggest that their problem-solving skills are impacted through modified homework assignments and the additional opportunities to interact with one another and instructors in tutorials and help sessions.

Why might such an initial effort have shown such success? One reason may be that instructors had more opportunities to gain insight into student thinking at a depth not typically available. Several aspects of the course—particularly clickers, tutorials, and homework help sessions—allow the instructor to listen to student reasoning. One (non-PER) instructor contrasted the new materials with a traditional course: “What you tend to do teaching in the traditional way is, there are three or four students, maybe only one sometimes, who's on top of everything, answers all the questions, is smiling, is happy, and you get a rapport with the students who talk to you and you feel like things are going great.” The developed materials (clicker questions, tutorials, and homework help sessions), he claimed, help him to “talk more directly to and hear, listen to, the average student.” This additional insight into student thinking allows instructors to appropriately adjust instruction, an outcome cited by many instructors in interviews. “I know whether the students understood what I just said, for instance, or whether I screwed up,” explained one instructor, regarding the use of clickers. Tutorials and homework help sessions offer a similar opportunity: “On the whole it's let me have really more communication with the class, to have a better sense of what's going on with them than I would have otherwise,” explained another, regarding homework help sessions.

Another reason for the success of this approach may be that the materials instigate a change in classroom culture. One instructor (teaching a similarly transformed quantum mechanics course²⁷) indicated that clickers helped to frame the class as an interactive environment, essentially breaking the ice so that it was easier to generate conversation in the class. Thus, because students were encouraged to participate through a variety of methods, the door was opened towards a more student-centered classroom culture. Students participated in

active practice and application of physics, where they received support from peers and experts. While research may point the way toward further improvements in this area, this approach appears to be the first step in the goal of supporting the next generation of physics students as they work toward more sophisticated levels of scholarship and thought.

We wish to outline some considerations for an instructor who would like to use these—or other—materials in their course. Simply using all the course elements does not guarantee a successful implementation, as suggested by our observations that lower fidelity to the course transformations was associated with lower learning gains.¹¹ The benefits of using instructional techniques are not automatic; implementation appears to make a difference. For example, instructors implement clicker questions in various ways,²⁸ and the outcomes from interactive engagement are variable,²⁹ presumably due to variations in implementation. An instructor must carefully consider the rationale behind the different course elements when deciding whether to adopt and/or adapt the materials to their needs.

Student buy-in is also important.³⁰ In one section (PER-A), both learning gains and student attitudes were less favorable. In this case, we see evidence of a lack of student buy-in, which may have partially sabotaged the course approach, leading to poor student engagement and evaluations of the course. Thus, instructors considering such a change of course approach might consider how to create a positive climate for student engagement by explaining why this course approach will be used, for example, or taking the pulse of the course through a short survey in the first few weeks.

Our materials would certainly benefit from continued development. Student scores on the CUE leave room for improvement and we did not affect outcomes on traditional exams. Students were positive about the lecture parts of the course, but their attitudes are not as positive as we would have expected on certain measures, and many complaints mirror those in traditional classes. Additional research on student difficulties at the junior level would be valuable to future transformation efforts, as well as to the community of upper-division physics instructors.

More broadly, it may be that the model of course reform that has proved effective at the introductory level—clicker questions, homework, and tutorials aimed at conceptual understanding—only takes us so far. At the introductory level, at CU more extensive reforms (e.g., clickers, tutorials, and learning assistants) result in higher learning gains than modest transformations (e.g., clickers alone).³¹ It may be that our techniques aren't the "right level of radical" for this population. These students are more motivated, skilled, and mature than introductory students. Clicker questions and tutorials provide a high level of guidance—asking students to choose between pre-determined answer choices or to follow a set of guided procedures. Rather, we may more successfully achieve our learning goals if students begin to generate their own answers to open-ended questions or to generate the questions themselves as in the innovative techniques in the Paradigms courses at Oregon State University.³² While the efficacy of Paradigms remains untested, the model is intriguing in suggesting the "next step" in our own reforms.

Success in upper-division physics requires a great deal from our students. These students are required to use recently gained, sophisticated mathematical tools in application to problems of previously un-encountered complexity. The

intellectual challenge—which students often say is one of the first tastes they receive of what it means to "do physics"—can either deepen a student's dedication to the field or discourage her from pursuing it further. But just because these courses serve this selection function does not mean that minimal guidance is the best method to identify the students who can make physics a part of their careers. Our traditional courses appear to do a relatively good job of teaching calculational skill. The transformed course, additionally, attempts to address the concepts, process, and habits of mind of the upper-division course in a more fully supported way.

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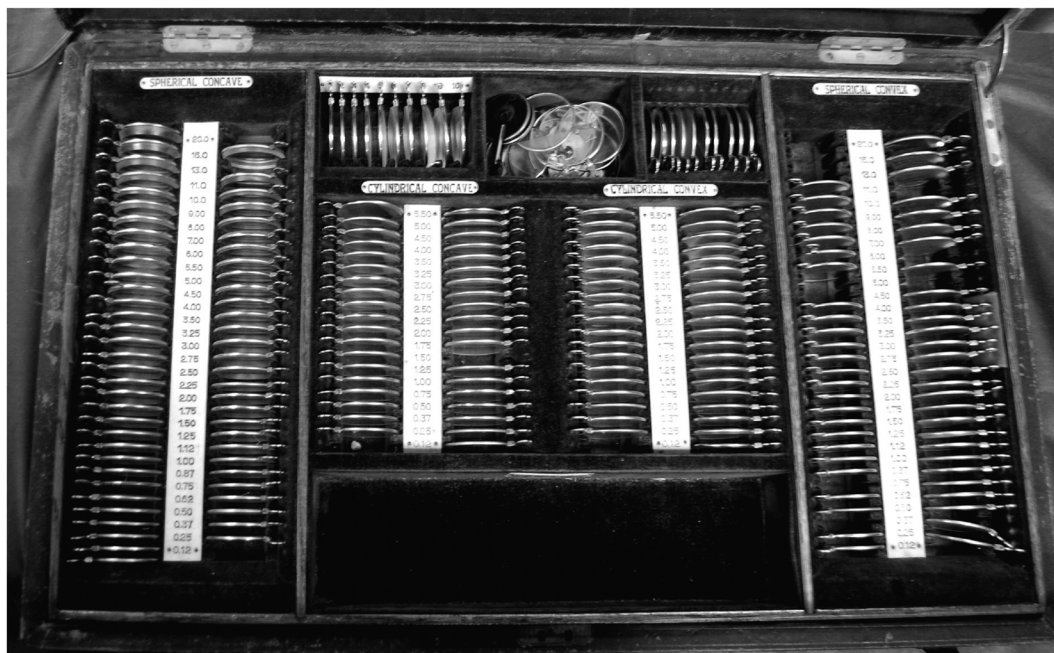
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Optician's Lens Set

When you have your eyes tested today, all of the trial lenses are contained in wheels that are rotated in front of your eyes. In the earlier part of the twentieth century, the lenses were taken from large sets like this one at Creighton University. Each lens had a handle into which was punched "+" or "-" to indicate whether the lens was converging or diverging, plus a number to give the power of the lens in diopters. (Notes by Thomas B. Greenslade, Jr., Kenyon College, photograph by Vacek Miglus, Wesleyan University)