To be published in the Proceedings of the Physics Education Research Conference 2009

A Research-Based Approach to Assessing Student Learning Issues in Upper-Division Electricity & Magnetism

Stephanie V. Chasteen[*†] and Steven J. Pollock[†]

[*] *Science Education Initiative, University of Colorado, Boulder, CO 80309, USA*
[†] *Department of Physics, University of Colorado, Boulder, CO 80309, USA*

As part of our efforts to systematically improve our junior-level Electricity & Magnetism I (Electro- and Magneto-Statics) course, we have developed a conceptual instrument, the CUE (Colorado Upper-division Electrostatics) diagnostic. Two central goals of this tool are: to assess impacts of transformed curricula, and to systematically identify and document student learning difficulties. We find persistent issues involving students' ability to conceptually approach and visualize E&M, to accurately communicate that understanding, and to appropriately identify and apply upper-level problem-solving strategies. Our work underlines the need for further research on the nature of student learning – and appropriate instructional interventions –at the upper division.

Keywords: physics education research, course reform, electricity and magnetism, assessment
PACS: 01.30.Ib, 01.40.Di, 01.40.Fk, 01.40.G-, 01.40.gb

INTRODUCTION

The PER community has established a large and growing research base which includes developing and evaluating curricula to improve our teaching. In the field of electromagnetism (E&M), much effort has focused on the introductory level[1], including assessment[2], but less attention has been focused on the upper division[3]. At CU Boulder, we are engaged in a long-term effort to extend PER methods to investigate junior-level E&M[4]. This work involves three strands: articulation of learning goals in collaboration with a broad cross-section of faculty, development of materials and teaching practices to address those goals, and construction of appropriate assessment tools.

Here, we present initial results arising from our development of the Colorado upper-division Electrostatics assessment (CUE.) The CUE serves multiple purposes. First, it provides direct measurement of a range of course goals valued by working faculty. Much as the FCI provides a "litmus-test" of the effectiveness of lower-division introductory courses, the CUE may serve as a comparative instrument to assess upper-division E&M *courses*. Second, the questions are designed to seem straightforward to our colleagues who regularly teach this course. Thus, poor performance by students may encourage faculty to pay more attention to their own goals and teaching methods. Third, the open-ended nature of CUE questions provides a means to elicit and examine a variety of aspects of student ideas. This yields opportunities for education researchers to learn more about specific areas where upper-level students are struggling. Such deepened understanding is a prerequisite for meaningful course reforms. In this paper, after a brief introduction to the CUE, we focus on a few select topical and procedural areas of student difficulties uncovered by the CUE. This work is preliminary, and intended more as a demonstration of the potential of this instrument than as a summary or outline of outcomes. We hope to encourage other faculty to extend this work, as the community expands its focus on upper-division transformations.

METHODS

Learning goals for the course were developed in a series of meetings with a group of PER and non-PER faculty. These learning goals externalize implicit expectations that faculty believe junior-level physics students should gain in this and other upper division courses, such as "choose and apply the appropriate problem-solving technique" and "sketch the physical parameters of a problem."[5] These goals guided development of the CUE and course-reform approach.

The CUE is a 17-question test (15 questions on electrostatics, and 2 questions on magnetostatics) testing students' performance on the learning goals of

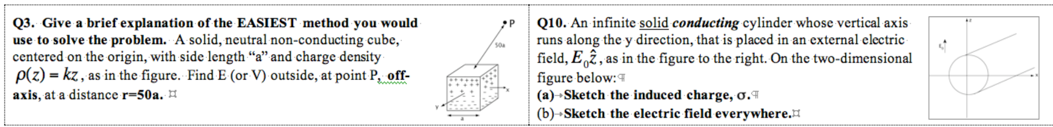

FIGURE 1. Two problems from the CUE, Q2 (5 points) and Q10 (10 points). Total exam is worth 118 points.

the course: ie., to choose a problem-solving method and defend that choice, sketch electric field patterns, graph electric field strength and potentials, and explain the physics and mathematics underlying steps in common problems. With the exception of one multiple-choice question the exam is open-ended; 3 additional questions give students a multiple-choice alternative and require students to explain their answer to receive credit. Fig 1 shows two sample questions from the CUE[6]. The CUE and its rubric were validated, and we find good inter-rater reliability[7].

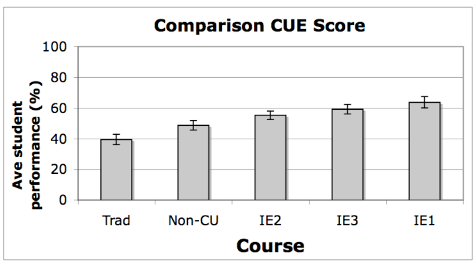

FIGURE 2. Comparison CUE score consisting of questions given in common between courses (Total N=203). "Trad" (N=26) is a lecture-based course at CU, IE1-3 (N=21, 48, and 27) are CU courses using research-based transformations, "Non-CU" (N=91) is the average of two lecture courses at a public university not using CU materials.

The CUE was given in-class to 203 students in 4 semesters at the University of Colorado (CU) and 5 non-CU courses[7,8]. Comparison CUE scores for 5 courses with N>20 are shown in Fig 2. Students in courses using transformed curricula (ave 51.9%) perform better than those in courses not using the new materials (ave 46.1%; $p<0.05$). Given this, and the correlation of CUE scores with course grade (Pearson $r=0.49$, $p<<0.01$), the CUE appears to measure differences valued by faculty and researchers.

STUDENT PERFORMANCE

The CUE taps into at least four learning goals for the course, which we categorize in Table 1.

TABLE 1. Learning Goals addressed by the CUE.
Due to slightly different versions of the test, the number of questions varies slightly by course (generally "Trad" consists of 1-2 questions fewer than the IE courses).

Learning Goal	Description	# of distinct CUE Questions
1. Math/Physics connection	Physical meaning of equations	3
2. Visualizing the problem	Sketching, graphing	3
3. Communication	Explanations and justifications	9-11
4. Problem-Solving		
(a) Appropriate method choice	Correct method choice for the problem	6-7
(b) Techniques and skills	Superposition, Approximations, Symmetry, Sep. Vars.	12-14

Figure 3A shows student scores on these different learning goals. Performance in all areas is low (rarely over 60%), though students in the transformed courses do better overall. This is a challenging test. The CUE was also given at a small liberal arts college (N=12); those students were better prepared (as measured by a CUE pre-test) and performed 10-20% better than the average of CU IE courses on all areas except Math/Physics Connection. Thus, it is possible for some student populations to perform well on these measures.

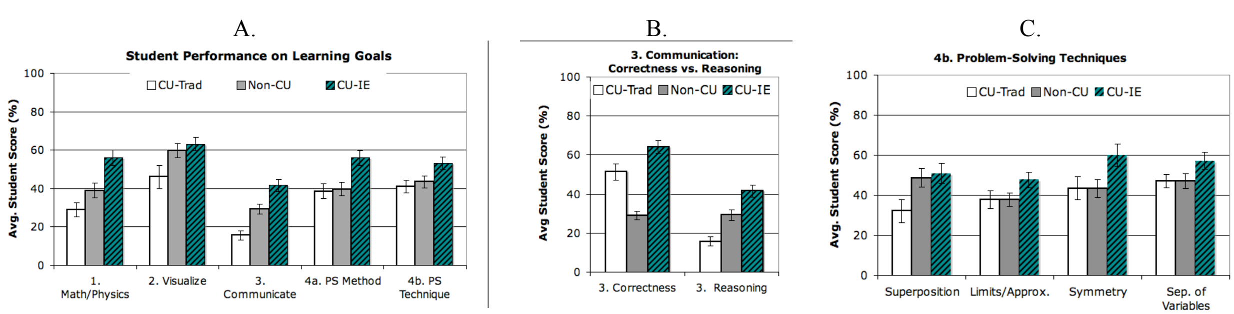

FIGURE 3. (A) Student performance on Learning Goals. "Ave IE" is the average of transformed CU courses IE1-3. All questions are given equal weights for purposes of this analysis, regardless of the points they contribute towards the final CUE score. (B) Communication score compared to correctness score. (C) Problem-solving techniques broken out by category.

Communication: Reasoning

One learning goal that students struggle with in all courses is that of Communication. This set of questions required students to choose an answer, and then to justify and explain it (eg Q3, in Fig 1). In all such questions, the "correctness" of the answer (did they choose the right problem solving method, did they choose the correct multiple choice response) was coded and graded separately from their explanation. This allows us to separate the quality of the explanation from the factual content knowledge (Fig 3B). In all courses, there is a marked difference between students' ability to correctly answer the question (e.g., "Dipole Approximation" for Q3) and their ability to satisfactorily explain or justify their choice (e.g., "You are far away from the cube, so the dipole is a good approximation; lack of symmetry for using Coulomb's Law.")

There are many types of explanations that students give. Using Q3 as an example, some explanations were insufficient ("because it looks like the monopole term would be zero," "looks like dipole"), used inappropriate equations ("$\nabla^2 V = 0$ and then $E = -\nabla V$") or simply gave incorrect or partially correct answers ("direct integration, no symmetry"). A more complete explanation, for example, would be "distance is great enough to just use dipole"

These results are not surprising, as students' answer-making skills are typically cultivated more strongly than their ability to explain. Additionally, many students in the traditional course simply wrote the name of the method (e.g. "Multipole Expansion") without any explanation for their choice of strategy. It's difficult to determine whether improved performance on these questions is due to (a) enhanced conceptual understanding, or (b) increased value placed on reasoning skills in the Transformed course .

Visualization

Two questions ask students to graph or sketch. Students perform better on this learning goal but even here there are significant difficulties. One such question (Q10) asks students to sketch the E-field outside an uncharged metal cylinder placed in a uniform external E-field. Students score an average of 62% on this question. Some example student responses are given in Fig 4, below. Students are, for the most part, able to correctly sketch the charge distribution *resulting* from the external field (81% average score), but finding the resulting field proves more difficult. They often fail to correctly superpose E-fields to obtain the full E-field outside (19% draw a constant E_0 outside), or incorrectly show nonzero E inside the conductor (40% of students). Students draw on a number of resources about polarization, shielding and superposition, including remembered sketches (e.g. dipole pattern and magnetic field pattern) or rules (such as E=0 inside). But they often miss the desired synthesis of physical intuition (how would they expect a charged particle to behave in this situation?), or consistency at the boundary, that faculty seek to teach.

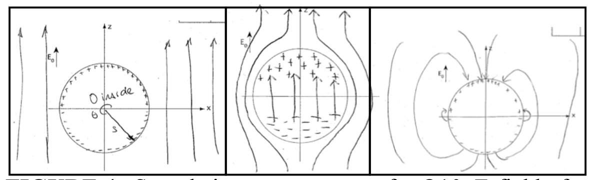

FIGURE 4. Sample incorrect answers for Q10: E-field of metal cylinder in external E_0.

Problem-solving skills

The learning goal "Students should be able to choose and apply the problem-solving technique that is appropriate to a particular problem" is a central tenet of our upper-division courses. Most questions on the CUE can be characterized as falling under the rubric of "problem solving" to some degree. We broke these questions into two parts: (a) "choosing the right problem solving method", and (b) "demonstrating understanding of a problem-solving technique/skill".

Choosing the right problem solving method

Seven questions require students to extract the central features of a problem and recognize which solution method will best fit the problem at hand. For example, Q2 asks students how to solve for E of a charged cube (same physical situation as the one shown in Fig 1, Q3) when point P is *on*-axis and *close* to the cube. To arrive at the correct answer ("direct integration, with Coulomb's Law") the student has to recognize that, while the problem is symmetric, that symmetry is not of the appropriate type to use Gauss' Law. They also must recognize that because the point of interest is close by, the dipole term of the multipole expansion will not yield an accurate approximation. However, among the 203 students whose results are reported in Fig 3, these are the most common incorrect responses: 19% answer "Multipole Expansion" and 13% of respondents choose "Gauss' Law." Only 42% of students received full credit.

When point P is moved off-axis, and far away, only 32% of students get full credit for their choice of method (though 57% do mention dipole or multipole in some way), with 22% again answering "direct integration" (which receives partial credit). Thus, students struggle with extracting the general features of problems when they are out of the context of an exam or homework on recent material. On the CUE and in student interviews, students demonstrate strong use of formal methods, but novice-like conceptual organization. They are frequently unaware when a given method is *not* appropriate, with over-reliance on mathematical formalism ("Just do the integral!")

Problem-solving techniques

We break problem-solving *techniques* down into several subcategories, e.g. superposition (3 questions), limits/approximations (3-5 questions), symmetry (2 questions), and separation of variables (4 questions). As an example, "Limits and Approximations" consists of the following questions:

- Q3 (Fig 1): Solve for E (or V) above a dipole-like cube when P is very far away and off-axis
- Q6: Solve for B (or A) above a current loop
- Q9 (Fig 1): Determine the sign of V in the limit that $r \rightarrow \infty$ from a positively charged sphere
- Q12: The value of E of a charged disk for $z \ll R$ and the functional dependence of E on z as $z \gg R$.
- Q14: State how the properties of a capacitor change in the limit that the inserted dielectric becomes a conductor

In both Q3 and Q6, students fail to recognize the implications of the choice of an observation point that is (a) far away and (b) off-axis. The fact that the observation point is off-axis implies that direct integration will be particularly challenging, yet many students fall back on this "failsafe" method of problem solving: 22% for Q3 and a full 40% for Q6 (perhaps due to the decreased familiarity with a current loop as a dipole). However, a physicist will recognize that the choice of an observation point that is far away suggests a much easier method – that of the dipole approximation. Yet only 57% of students mention multipole or dipole in their answer for Q3, and just 25% for Q6. Indeed, many students who answered "Multiple Expansion" or "Direct Integration" for when the point was close to the cube answered "same thing" when the point was far away.

In Q12, a surprising number of students fail to evaluate the E-field of a disk when $z \ll R$ (infinite plane; average score 43%) and when $z \gg R$ (point charge; 59%), with large variation by instructor. For $z \gg R$, some students fail to give the functional $1/z^2$ dependence required for full credit, stating correctly but incompletely just that it goes to zero. This error points to student misunderstanding of what we mean by "limiting form," and serves as a guide to instructors trying to help students improve this type of skill.

For $z \ll R$, some students get lost in calculations as they attempt to solve Gauss' Law for a plane of charge. Several students state that E goes to infinity as $z \ll R$ – an error repeated when they sketch E for the disk – 27% draw an E-field which is infinitely valued at z=0. Thus, many students still do not differentiate between point charges and an idealized surface charge (which has no singularity at the origin). Overall, students appear to require additional support in developing a broad number of essential physicists' skills, which faculty may assume are present or naturally develop in this course.

CONCLUSIONS

Through administration of the CUE, we begin to identify several serious difficulties with the skills expected of junior physics students. While interactive, conceptually-based curricula improve student performance on our learning goals, improved instructional techniques are still needed to support students' ability in these areas. We note problems in communicating understanding to others, visualizing fields, choosing and applying sophisticated problem solving techniques, and appropriately using skills such as limiting forms. This paper shows the potential of the CUE to assist us in investigating student thinking, through analysis of student responses. This work will be extended in more detail in future publications.

ACKNOWLEDGMENTS

We acknowledge the generous contributions of many faculty members at CU and elsewhere, for assistance with creating and/or administering the CUE. This work is funded by the Science Education Initiative and NSF-CCLI grant #0737118.

REFERENCES

[1] E.g., C. Singh, *Am. J. Phys.* **74**, 923 (2006); L. McDermott and E. Redish, *Am. J. Phys.* **67**, 755, (1999) and references; R. Chabay and B. Sherwood, *Am. J. Phys*. **74**, 329 (2006).
[2] D. Maloney et al, *Am. J. Phys.* **69** (2001) S12; L. Ding et al., *Phys Rev ST:PER* 2, 010105 (2006)
[3] For example: C. A. Manogue, et. al, *Am. J. Phys.* **74**, 344 (2006); J. Bilak and C. Singh, *PERC Proc. 951*, AIP , Greensboro, NC, 2007, p. 49; T. J. Bing and E. F. Redish, *PER Proc 883*, AIP, Syracuse, NY, 2006, p. 26.; E. F. Redish, *World View on Physics Education in 2005, Focusing on Change Conf. Proc., Delhi 2005.*
[4] S.V. Chasteen and S.J. Pollock *PERC Proc. 1064*, AIP, Syracuse, NY, 2008, p 91-94.
[5] All course material (e.g., learning goals, clicker questions, CUE) are at www.colorado.edu/sei/departments/
[6] To see the CUE and provide feedback, visit www.colorado.edu/sei/surveys/Faculty/CUE/Sp09_CUE.html
[7] Chasteen, S.V. and S. J. Pollock, PERC 2009 (submitted).
[8] Because the CUE was modified from semester to semester, the "Comparison CUE" (88 points out of 118) is made of questions given in common across all exams.