The use of concept tests and peer instruction in upper-division physics

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Abstract. Many upper-division courses at the University of Colorado now regularly use peer instruction in the form of clicker questions during lectures. Particular attention has been paid to developing and implementing clicker questions in junior-level E&M and Quantum mechanics. These transformed classes largely follow traditional local norms of syllabus and content coverage, but are designed to address broader learning goals (e.g developing math-physics connections) that our faculty expect from physics majors in these courses. Concept-tests are designed to align with these goals, and have altered the dynamic of our classes. Coupled with other course transformations, we find measurable improvement in student performance on targeted conceptual post-tests. Here, we discuss classroom logistics of upper-division clickers, purposes of clicker questions, aspects of student engagement facilitated by concept-tests, and observations of and challenges to sustainability of this activity.

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

INTRODUCTION

Much PER research has focused on improving the teaching of introductory physics, with significant and growing evidence for the value of explicitly interactive teaching methods[1,2]. At the upper-division level, less research has been done, but here too a growing body of evidence indicates that students can benefit from interactive engagement in the classroom[3,4]. At CU Boulder, faculty have collectively discussed course-level learning goals, and we have modified several upper-division courses to include materials and methodology designed to support those goals, while simultaneously improving conceptual post-test outcomes[4]. Here, we discuss one of the most visible changes in these class settings; the use of concept tests and peer instruction. This pedagogical tool has a high level of support among students and faculty in a broad range of courses at CU[5]. We describe the approach and outcomes, with a focus on connecting these class activities to our consensus learning goals, in the specific context of the first semester of an upper-division Electricity and Magnetism (E&M) course.

CONSENSUS LEARNING GOALS

Starting in 2007, we held a series of brown bag lunches for physics faculty interested in developing course-level learning goals for our upper-division E&M class. More than a dozen faculty, along with PER faculty and postdocs, participated. These goals represent what we want students to be able to *do* at the end of the course (as opposed to what *content* is expected to be covered, as in a syllabus). A highly abbreviated summary follows[6]. In all items below, "..." should be read "A student should be able to...":

1. ***Math/physics connection:*** *...translate a physical description to a mathematical equation, and conversely, explain the physical meaning of the mathematics.*
2. ***Visualize the problem:*** *...represent key aspects of physics through sketches.*
3. ***Organized knowledge:*** *...articulate the big ideas from each chapter, section, and/or lecture.*
4. ***Communication.*** *...justify and explain their thinking and/or approaches, both in writing and orally.*
5. ***Problem-solving techniques:*** *...choose, apply, and justify appropriate problem-solving techniques in novel contexts, including (a) approximations and series expansions, (b) symmetries, (c) multivariable integration and PDE setup, (d) superposition.*
6. ***Problem-solving strategy:*** *...organize and carry out long, complex physics problems.*
7. ***Expecting and checking solution:*** *...articulate expectations for, and justify reasonableness of solutions*
8. ***Intellectual maturity:*** *...be aware of what they don't understand, evidenced by asking sophisticated, specific questions; articulating where they experience difficulty; and taking actions to move beyond that difficulty.*
9. ***Maxwell's Equations: ...*** *see the various laws in this course as coherent, and use Maxwell's equations in differential and integral form to solve problems.*
10. ***Build on earlier material.***

These goals reflect components of our collective sense of what skills are required to "think and act like a physicist" at this (junior) level. They informed and guided development of our course-reform approaches, including the use and content of clicker questions.

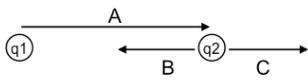# IMPLEMENTATION OF PEER INSTRUCTION IN UPPER-DIVISION

The utility of clickers and peer discussion in introductory classes is well-established[2,7]. In our upper-division courses (~20-60 students), the implementation details vary somewhat across faculty. Typically 2 to 5 multiple-choice clicker questions were used per 50-minute lecture, with student discussing amongst themselves before voting. Faculty then facilitated a discussion, focusing on articulation of reasoning and arguments, hearing multiple voices, and scaffolding productive argumentation.

Examples of clicker questions

Clicker questions may include conceptual puzzles, steps in derivations, applications to new contexts, or explicit sense-making. Below, we present a few questions from an implementation of our junior-level E&M course, covering roughly the first 6-7 chapters of Griffiths' text[8]. We follow each example with a brief summary of relevant parts of the class discussion, and explicit connections to our broader learning goals. In the following section, we discuss different instructor experiences with clicker questions.


FIGURE 1. Griffiths' "curly R" notation.

The question in Fig. 1 was given in the first lecture, immediately after introduction of Griffith's "curly R" notation. *All* 5 choices received votes. Coulomb's law is familiar, freshman level material (goal 10), but the new notation proved challenging throughout the upper-level course. This question addressed the notation, relating it to a mixed, spatial representation (goals 1 and 2.) The correct answer is D (only 1/3 of students got this), since either vector A or C could

potentially be right - the length of a "unit" vector doesn't translate to a physical length in this picture.

Discussion points arising from students (goal 8) included the direction of the arrow (students defending answer B were convinced they were wrong by other students, using the definition of $\vec{\mathfrak{R}}_{12}$ on the board, goal 4). Some students argued that the unit vector is mathematically well-defined by geometry (thus, E is incorrect. It took a few minutes of student discussion for them to come to consensus on this point). There was argument that A must be wrong because q_1 and q_2 are 2 m apart, but a unit vector should only span 1 unit of distance, which generated a nice discussion of the (slightly ironic) unitless nature of unit vectors, and thus their "length" on this figure is arbitrary. Several students questioned the significance of the location of the arrow on the page, a freshman idea that turned out to be lost for some of these juniors (goal 10).
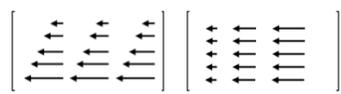
FIGURE 2. An introductory question on math-physics, and the conditions of electrostatics problems.

The question in Fig 2 came after formal discussion of both Gauss' law and the fact that $\nabla \times \mathbf{E}=0$ in electrostatics. We chose this problem to encourage students to relate mathematical formalism to graphical representations, to help students visualize and make sense of "curl" beyond formulaic computation, and to encourage thinking about the physics of different situations (goals 1, 2, and 7). We anticipated that students might not see that the field on the left had a non-zero curl, but this was not a problem for over 2/3 of the class. Instead, their focus was on field II. The ensuing conversation ranged across a variety of important topics. Some students wondered whether we should assume the region was charge-free or not, leading to a discussion of relating $\nabla \cdot \mathbf{E}$ to charge density (Gauss' law in differential form, goal 9), and "visually computing" the divergence (goal 1). Many students began debating what charge distribution could generate such a field - some interpreted this as the field near a line charge off the page to the right, which they remembered from freshman physics (goal 10). This led to a fruitful discussion of implicit assumptions (this figure is ambiguous with respect to

behavior in the 3rd dimension). Others thought this was the field in an "unbalanced capacitor", with a large highly charged + sheet on the right, and a more weakly charged - sheet on the left. This (incorrect) idea was articulated and argued by students through the room (goals 4 and 8) and ultimately consensus arose that the proposal was inconsistent with Gauss' law. In all, well over 10 minutes of class time were spent on this question, far more than a traditional lecture would likely have devoted to what appears to be a straightforward question, but a significant fraction of our learning goals were elicited and addressed.

FIGURE 3. An example from later in the term, on Laplace's equation and separation of variables.

This example (Fig 3) came later in the term, when solving Laplace's equation in Cartesian coordinates with separation of variables. The text, and lead-in lecture, works through an example much like this. We knew that the "0 to 0" boundary would likely elicit a rote (and correct) answer, but wondered if the "V_0 to V_0" would complicate the issue, which is precisely what happened. Discussion included a vague "symmetry" argument (which led many students to incorrectly answer C). Resolution came when they were asked to follow through on answer C, and work out what this implies for the solution (goals 5b, 5c). Here, the emphasis was on using formal mathematics to follow up on their qualitative, conceptual arguments (goal 1 and 7). We followed this question by a nearly identical one in which all four sides had potential V_0. Most (75%) of the class incorrectly voted D (it "doesn't matter"). Here we were able to push them to defend their mathematical intuition with physical understanding (goal 1). The instructor reminded them of the uniqueness theorem and asked if they could come up with any solution. The class quickly and collectively converged on "V=constant throughout", and that this required answer C. (At the start of the next lecture, we began with the same question and the class was now 100% correct, with clear reasoning articulated.)

The question in Fig 4 asks students to make a qualitative interpretation of a very formal expression.

Even after peer discussion, the fraction of the class getting this challenging question correct was small.
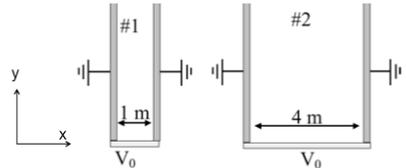

FIGURE 4. Follow-up on separation of variables.

Most voted for A, "the same", by a vaguely articulated and incorrect symmetry argument (in both cases it is the "middle of the well", and in both cases the same height above the bottom). The ensuing discussion included both a mathematical approach (goal 5a, considering the exponential term in the two cases, recognizing that the dimension "a" sets the distance scale for exponential decay in the vertical direction) and a physical approach (goals 1 and 7, considering limits, as the width gets larger).

INSTRUCTOR EXPERIENCES

As part of our transformation efforts, all recent faculty in upper-division E&M were interviewed. The discussions and examples above were largely drawn from the initial implementation (taught by SJP, averaging 3.5 clicker questions/lecture), but data from subsequent terms are consistent, albeit with variations. Because the clicker questions form a key part of the course approach (i.e., integrated scaffolding of students' skills in sophisticated thinking about physics), we examined faculty experiences in implementation of clickers. Other course aspects (homework, tutorials, etc.) are discussed elsewhere [4]

All faculty noted the value of clicker questions in terms of getting in touch with student difficulties and ideas. Prof. C (novice instructor, 3.3 quest./lect.): "I'm completely convinced about the clicker questions. It's very useful in many ways. I know whether the students understood what I just said... or whether I screwed up." Prof. D (first time teaching the course, 2.5 quest./lect.): "doing the concept test questions, it lets me... listen to the average student...and it lets me focus my attention much more on them... it's let me have really more communication with the class, to have a better sense of what's going on with them that I would have." Many faculty indicated surprise at difficulties revealed by concept tests, e.g. Prof. C: "the first one was really low, like 30%... I was glad we went over it."

A related observation centers on the clicker questions as being perceived as valuable to *students*, consistent with our goals (both 4 and 8) of facilitating a collaborative classroom culture. Prof B (highly experienced instructor, 3.1 questions/lecture): "it kept them also engaged so they didn't turn off", and "clicker questions...helped the students understand whether they were getting the point or not". Prof B also reported that students were more positive, and discussed more in class, than in any upper division course he had ever taught. Prof D: "it is really that they learn through the discussion... that's more motivating for the peers than if I say why the answers are wrong.". Prof. E (novice instructor, 2.5 questions/lecture): "The clicker question have helped a lot ...because we got some interaction. In the beginning I had maybe three or four clicker question per lecture. Now I don't need this any more to get interaction with the students."

Faculty also discussed challenges. Prof. A (PER-faculty, experienced in lower-division but new to upper-division, 4.2 questions/lecture) raised an issue of pedagogical philosophy - he preferred to first lecture, and then support content through concept questions, rather than allowing concept questions to develop content. He also pointed out, "concept tests are great, but they're never exactly what I want them to be, so I'm glad that I have the originals and can edit them to taste." Prof. B stated, "Giving other people's concept tests is ... really scary, because you just never know if somebody verbally added a qualifier that makes it clear what was meant and you don't know that that qualifier is necessary". All faculty reported modifying or adding their own clicker questions, e.g. Prof. C: "sometimes I find no clicker questions about [a topic], so I make a clicker question on this".

Many faculty brought up the value of having clicker questions (and other materials) organized and available. Prof D: "[materials] allow the interested person to start teaching a transformed course without the huge time investment that it might otherwise have to require to go into this", although Prof C adds: "I think this course is going much better than it would go without all these materials, even though it doesn't really save time for me."

DISCUSSION

Upper-division physics requires lengthy calculations and sophisticated problem-solving skills. This involves mathematical facility along with conceptual understanding, an array of sense-making tools, and a broad base of content knowledge. We introduced clicker questions in our upper division E&M course three years ago, and they have been consistently popular with both students and faculty in this and other classes[5]. Our materials have also been used at other institutions, and clicker questions are the #1 adopted material, suggesting they provide a low-barrier and easily transferable pedagogy[9], with room for faculty creativity and modifications. Faculty who used clicker questions stated that this pedadogy gave them insight into how students are thinking and whether students are achieving course-level learning goals, along with a mechanism to allow them to more fully support student development. Thus, this pedagogical tool may implicitly support instruction targeted to the course learning goals.

Conceptual questions in the context of lectures provide a mechanism to develop, observe, and facilitate student use of problem-solving tools. But, simply asking concept questions is not enough. Student discussion is key to achieving our high-level consensus learning goals, and the ongoing development of sophisticated physics reasoning skills. The pedagogy of peer instruction takes advantage of social elements of learning, makes student reasoning and argumentation visible to both faculty and students, and allows faculty to explicitly acknowledge the importance of conceptual reasoning and argumentation.

ACKNOWLEDGMENTS

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