Enhancing Active Learning in Large-Enrollment Physics Courses

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IINTRODUCTION

I have taught physics courses for physics majors, engineering students, and life-sciences majors, as well as for students planning careers as public-school teachers in both elementary and secondary schools. A common theme in all of these courses is "active learning," that is: guiding students to maximum intellectual engagement with the material. A key strategy is to promote intensive interaction both between students and the instructor, and among the students themselves. This holds true whether one has a dozen elementary-education majors in a lab room, or 200 engineering students in a large lecture hall.

Much research suggests that learning of science concepts is enhanced when students are guided to analyze and draw conclusions from their own observations of physical phenomena (McDermott, 1991). Instead of instructors providing worked-out solutions and pre-packaged explanations, students are guided to "figure things out for themselves" with a minimum of intervention. When an instructor is working with just one or two students, this task might be relatively easy to accomplish. But when one faces 100 or more students simultaneously, the challenge of promoting maximum intellectual engagement can be extreme.

In this paper I describe methods I have used with great success to promote active learning in large-enrollment physics classes. The strategies are based on *guiding students along productive lines of reasoning through a question-and-answer process in a group-learning environment.* In a different context I have used this same strategy in small classes for pre-service elementary teachers. Although the specific techniques described here might differ from those used in a small class, the overall strategy is essentially the same: help students learn efficiently by aiding them to ask and answer intellectually provocative questions. The goal is to catalyze, in the students' own mind, the conceptual breakthroughs needed for understanding of scientific concepts.

THE PROBLEM: LARGE CLASSES

Imagine you are beginning your lecture in a room filled with 150 students. Many of them—perhaps most—appear to be attentive and expectant. You start your carefully prepared presentation, striving to be as clear as possible. Every now and then you ask a question of the class, pause and wait for someone to answer, and then comment on their response. Repeatedly, you ask if anyone has questions; only rarely does anyone respond. You're a bit uneasy about the lack of questions—surely they're not finding your explanations to be all *that* clear? You wonder how well your students actually understood your lecture. Were you able to clear up the tricky points you knew would cause them trouble? You can wait until the exam and see how well they do, but does this really tell you whether they got anything out of your lecture? For years, I wondered whether there was some way out of this frustrating dilemma. Eventually, I decided that indeed there was a way.

In the following paragraphs, I will describe methods developed in close collaboration with Kandiah Manivannan of Southwest Missouri State University (Meltzer and Manivannan, 2002a; Meltzer and Manivannan, 1996; see also http://www.physics.iastate.edu/per/index.html). I have used these methods primarily in the second semester of the algebra-based general physics course, a course taken mostly by students in the life sciences including pre-medical and pre-veterinary students. The majority of enrolled students are female. I have taught this course at Southeastern Louisiana University (Physics 192: Fall 1995-Spring 1998) and Iowa State University (Physics 112: Fall 1998-Fall 2002). Both institutions are typical in that their large student enrollments result in many large lecture courses. In physics, this means that an instructor teaching an introductory course might face anywhere from 50 to 250 students at one time. Both students and instructors are often dissatisfied with the “anonymous” atmosphere of such classes, and have a common interest in improving the effectiveness of the learning environment in these large lecture courses.

THE SOLUTION: INTERACTIVE ENGAGEMENT

Our basic strategy is to drastically increase the quantity and quality of interaction that occurs in class between the instructor and the students, and among the students themselves. To this end, the instructor poses many questions. All of the students must decide on an answer to the question, discuss their ideas with each other, and provide their responses to the instructor. The instructor makes immediate use of these responses by tailoring the succeeding questions and discussion to most effectively match the students’ pace of understanding. Our methods are, in effect, a variant of “Peer Instruction,” which was developed by Eric Mazur at Harvard University (Mazur, 1997; Crouch and Mazur, 2001). Instructional methods that emphasize interaction among students and instructors combined with rapid feedback have been referred to by Richard Hake as “interactive engagement” (Hake, 1998).

As a model of this learning environment, consider the instructor’s office. When you have one or two students in your office asking for help, do you lecture to them for 50 minutes, pausing occasionally to ask a question? More likely you speak for just a few minutes, sketching diagrams and writing a few simple equations. Then you stop and ask for some feedback. Maybe you pose a simple question or sketch out a problem for them to try, or ask one student to comment on an answer given by the other. In the office, you are able to get an ongoing sense of where your students are at conceptually, and how well they are following the ideas you’re presenting. By getting continual feedback from them, you’re able to tailor your presentation to their actual pace of understanding. By asking them to consider each other’s ideas, you help them to think critically about their own ideas. But is it practical to do this in a room filled with over 100 students?

My answer is that it *is* practical. It is possible to recreate in the lecture hall much of the learning environment that exists in the instructor’s office. One can transform—to a substantial extent—the environment of the lecture hall into that of a small seminar room in which *all* of the students are actively engaged in the discussion. It takes preparation and practice to do it well, but any instructor who is committed to the effort should be able to succeed. Here I will describe the methods I use in my large lecture classes.

THE FULLY INTERACTIVE LECTURE

To begin with, I give up the idea of delivering long lectures. As much as I used to love to lecture, I hardly do it anymore because I have become painfully aware of how ineffective it is. I used to enjoy carefully and precisely outlining my hard-won insights about difficult physics concepts. I would present these concepts slowly and painstakingly, with great clarity, never glossing over confusing points. As long as students were paying close attention, it was simply inconceivable to me that anyone could fail to follow my crystal-clear logic. Inconceivable, that is, until I really began to interact with my students in the lecture hall. I realized, to my dismay, that most of my students were *not* understanding my beautifully clear lectures—not at all. My carefully crafted arguments flew right over their heads, leaving only confusion. Sometimes they convinced themselves that they understood my words—but, in fact, they were usually wrong. What I did to discover that this was true any instructor can do, and I suspect they would come to a similar realization.

I now get instantaneous feedback simultaneously from all the students in the class. I ask questions during class—many questions—and no longer have to wait for one brave soul to dare to offer a response. Every single student in the class has a pack of six large "flash cards" (5½″ × 8½″), each printed with one of the letters A, B, C, D, E, or F. They bring the cards every day, and I always have extras in case someone forgets. Repeatedly during class I will present a multiple-choice question to the students. The questions stress qualitative concepts involving comparison of magnitudes (e.g., "*Which is larger: A, B, or C?"*), direction (*"Which way will it move?"*) and trends (*"Will it decrease, remain the same, or increase?"*). These kinds of questions are hard to answer by plugging numbers into an equation. I give the students some time to consider their response, 15 seconds to a minute depending on the difficulty of the question. Then I ask them to signal their response by holding up one of the cards, everybody at once. I can easily see all the cards from the front of the room. Immediately, I can tell whether most of the students have the answer I was seeking – or if, instead, there is a "split vote," some with one answer, some with another. (I hope that one is the right answer!)

I can see whether the class held up their cards quickly, with confidence, or if instead they brought them up slowly, with confused looks on their faces. If there is a split vote, I ask them to talk to each other. I allow about a minute for those who think the answer is, say, "A" to try to persuade those who believe it is "C" to change their views. And, of course, the "C" supporters argue for their side of the case. Then I ask for another vote. If it is still split, I'll ask for an "A" supporter to stand and present their argument, followed (in alphabetical order) by a proponent of the "C" point of view. Eventually, if necessary, I will step in to—I hope—alleviate the confusion. But by this time, most of the students will have thought through the concept that was causing the problem because they will have tried to convince their neighbors that they were right. And, if they haven't already figured things out by themselves, they will now at least be in an excellent position to make sense out of any argument I offer to them. Before that minute or two of hard thinking, though, I could have made the same argument and then watched as almost every student in the class gave the wrong answer to some simple question. I know this is true, because I have tried it often enough.

By now I have had many opportunities to ask my students questions during my lecture that I would once have considered “trivial.” These questions pertain to concepts that I—and most instructors—would have covered in a few seconds or a minute of clear, logical reasoning. I would have said that it was impossible for my students to get these simple questions wrong, or have any difficulty with them. But in fact they do, and now I know it. I pose a question that, I think, is a completely straightforward application of a principle I just presented. For instance: *If a two-resistor parallel circuit is increased to three resistors in parallel, what happens to the total power provided by the battery?* The logic points inescapably toward only one possibility. I wait as my students study the question, debating the answer with each other, looking around. Slowly, after a minute, the cards come up: half are “A” (decreases), and nearly a third are “B” (remains the same). But the correct answer is “C” (increases), a choice selected by perhaps one student out of five.

I realize that I need to retreat, and I offer another question—perhaps I make it up on the spot—that goes back to a concept discussed last week. Then we work our way through a series of intermediate questions, back to the one that started the trouble. At each step, I get a reading on my class: Do they respond quickly? With confidence? *Mostly* correctly? Then I comment briefly and move forward. Otherwise, I pause for a longer discussion. In the old days I would have disposed of this entire topic in less than two minutes of lecture, and have been well satisfied that I made my points clearly and effectively. Now I take 10 to 15 minutes, and struggle together with my students as they work their way through a conceptual minefield. But this time, I believe, my students really do construct a basis for understanding the material. And, I realize, the self-satisfaction of the old days was no more than wishful thinking and self-deception.

CLASS FORMAT

A typical class proceeds in three phases:

(1) A brief introduction/review of the basic concepts is presented at the blackboard, a sort of “mini-lecture” lasting three to seven minutes.

(2) A sequence of about a half-dozen multiple-choice questions (sometimes more) is posed to the class; these questions emphasize qualitative understanding, proceed from easier to more challenging, and are closely linked to each other to explore just one or two concepts from a multitude of perspectives. They frequently employ graphs, diagrams, and verbal descriptions. Students provide responses to these questions using the flash cards as described above.

(3) The students then proceed to work on free-response questions in the form of integrated worksheets, which again stress diagrammatic and graphical representations. The students work in groups while the instructor circulates throughout the room, rapidly scanning the students’ work by looking over

> their shoulder. It is easy to quickly assess the graphs, diagrams, and short answers that comprise the bulk of the responses.

This method is crucially dependent on having at one's disposal a large number of carefully constructed sequences of conceptual multiple-choice questions. The purpose of emphasizing non-numerical questions is to prevent students short-circuiting the thinking process by blindly plugging numbers into poorly understood equations. Although some collections of such problems exist in the literature (Mazur, 1997; Novak et al., 1999), we have had to construct our own set to meet the needs of a full one-semester course (Meltzer and Manivannan, 2002b). It is the preparation and testing of such question sets that is among the most time-consuming prerequisites for this instruction. Our questions are based, as much as possible, on the physics education research literature (McDermott and Redish, 1999).

The free-response questions are also presented in a highly structured sequence, designed to lead students to think deeply about fundamental conceptual issues. These worksheets are largely designed after the model of the University of Washington Tutorials (McDermott et al., 2002), although here adapted for large classes by somewhat more gentle pacing. Both the multiple-choice question sets and the free-response worksheets are provided to the students in the form of a three-hole-punched workbook, and they are required to bring relevant sections to class every day. I have also written a complete set of lecture notes which are now bound together with the workbook. These notes offer concise reference materials that heavily emphasize qualitative understanding, and provide numerous sample questions of the type used on quizzes and exams.

Another critical course element is the continual—almost relentless—feedback. Written quizzes are given every Monday and Friday and count for 1/3 of the total grade. Additional group-quiz points are available on Wednesday. Homework must be handed in during the Thursday "tutorial" (recitation) meetings. (Tutorials consist of group work on worksheets while two teaching assistants circulate throughout the room.) The net result of these incentives is a consistent 90% attendance rate for both lectures and recitations.

INSTRUCTIONAL OUTCOMES

I have found that overall learning gains by the students in this course are very high in relation to comparable courses nationwide. For the past several years I have given the "Conceptual Survey of Electricity," a diagnostic instrument that assesses qualitative understanding. My students' pretest scores (about 30%) are nearly identical to those reported in comparable algebra-based courses, and substantially lower than those in a nationwide sample of about 1500 students in calculus-based courses. However, the average post-test scores of my students in Physics 112 at Iowa State (taught five times from Fall 1998 to Fall 2002) were in the 75-79% range, while those of the nationwide sample range from around 43% in the comparable algebra-based course to approximately 51% for students in the calculus-based class (Meltzer and Manivannan, 2002a; Maloney et al., 2001). Other assessment data are consistent with these results. Moreover, on quantitative problems borrowed from exams given in the calculus-based course at Iowa State (Physics 221), students in my algebra-based course do comparably well, or better.

One of the most dramatic consequences of this instructional method is a very small number of dropouts, typically 1-3% after the first week. The low dropout rate combined with the strong evidence of good learning gains are, for me, the key test of the instructional methods. However, it is also important to note that the majority of students seem to react favorably to the instructional methods, as shown by their responses to end-of-semester surveys. Their feelings are reflected in their evaluations of the instructor and their comments on the instructional methods. From 1998-2002, 75% gave top ratings of 4 or 5 on a 1-5 scale. (Sample comment: *". . . best physics instructor I have ever had. I liked the way he had class interaction and explained things. He makes physics fun and interesting to learn, whereas most physics instructors just babble inanely during lecture"*). Most of the remainder are neutral, but a persistent core of 10% or less *despises* these methods and is vocal about that fact. (Sample comment from the same class: *". . . has a new way of teaching he is trying to develop. It doesn't work. He relies too heavily on the students to help each other, when all we want is to learn the material . . . going to lecture was pointless other than to take required quizzes."*)

CONCLUSION

The overall result of these methods is, for me, little short of a revelation regarding student learning. By exposing what I believe to be a realistic picture of how my students learn during lectures, I feel that I have been able to transform the classroom experience for them. Previously, this experience—while enjoyable for the instructor and (perhaps) entertaining for the students—served to do little more than inform them of the topics they needed to study on their own. I now believe that my students are actually *learning* during class, and building a much firmer basis for their out-of-class work.

My collaborator, Kandiah Manivannan, and I have given many workshops for other instructors to help them learn about our instructional methods, and we have published very detailed accounts of the methods that have been disseminated widely. Our CD of the instructional materials (Meltzer and Manivannan, 2002b) has been distributed free to many hundreds of physics instructors worldwide, on request, and many of them have told us that they have used our methods and materials successfully in their own classes. With support from the National Science Foundation, we are now engaged in developing additional materials for other topics in the introductory physics curriculum. We are hopeful that we will be able to achieve learning gains in other areas of the curriculum that are comparable to what we have documented in our previous work.

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