Enhancing Active Learning in Large-Enrollment Physics Courses

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Introduction

I have taught physics courses for physics majors, engineering students, and life-sciences majors, as well as for elementary education majors planning careers as public-school teachers. I have also taught courses for students preparing to teach secondary-school physics. A common theme underlying effective instruction in all of these courses is that of "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.

How can an instructor most effectively catalyze student learning of science concepts? Much research suggests that the students must be guided to work through extended chains of reasoning in their own minds, to observe physical phenomena and draw conclusions from their observations, and to "figure things out for themselves" with a minimum of intervention of the sort that simply provides worked out solutions and pre-packaged explanations. When an instructor is working with just one or two students, this task might be relatively easy to accomplish – assuming the instructor proceeds on the basis of this strategy. But when an instructor faces 100 or more students simultaneously, the challenge of promoting maximum intellectual engagement can be extreme.

In what follows I will describe methods I have used with great success to promote active learning in large-enrollment physics classes. The particular strategies are based on the idea of *guiding students to think deeply about targeted concepts through a process of question-and-answer in a group-learning environment.* In a different context I have used this same strategy in small classes for pre-service elementary teachers, and I believe that this pedagogical strategy is among the most effective for successful science instruction. The key is to get students to think hard about a difficult scientific concept, to guide them along productive lines of reasoning, and to assist them in making the conceptual breakthroughs necessary to achieve full understanding of the targeted concept. Although the specific techniques described here might differ from those used in a small class with students engaged in hands-on activities, the overall strategy is essentially the same: help students learn efficiently by aiding them to ask and answer intellectually provocative questions, the sort of questions that lead them to create in their own minds knowledge and understanding of scientific concepts.

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 any questions about what you have just said. It seems that no one does – or maybe just one or two people, and always the same ones. You're a bit uneasy about the lack of questions – surely they're not finding your explanations to be all ***that*** clear, are they? But you're doing the very best job you know how, and when you finish your lecture for the day you're satisfied that you did as well as anyone could reasonably expect.

So, how well ***did*** your students follow your lecture? Did they really understand the fine points of your arguments? Were you able to clear up the tricky points you knew would cause them trouble? ***How can you really know?*** Well, 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? Maybe they learned nothing in class, but figured it out themselves by reading the text. (In fact, if your class is typical, probably 50% or more of the students are not even there on an average day.) For years, I wondered whether there was some way out of this unending, frustrating dilemma. Eventually, I decided that indeed there was.

In what follows, I will describe methods developed in close collaboration with Kandiah Manivannan of Southwest Missouri State University (1). I have used these methods primarily in the second semester of the introductory general physics course, taught over the past seven years at Southeastern Louisiana University and Iowa State University. 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 100 to 250 students at one time. Students are often unhappy with the "anonymous" atmosphere of such large classes, where their individual questions may go unasked and answered. Instructors too are frequently dissatisfied with the very limited amount of individual attention they are able to provide in such a situation. Both have a common interest in improving the effectiveness of the learning environment in these large lecture courses, and that is the goal of these methods.

Our methods are, in effect, a variant of "Peer Instruction," which was developed by Eric Mazur at Harvard University (2). The 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. As a model of this learning environment, consider the instructor's office.

Think back to the last time you had one or two students in your office asking for help. Did you lecture them for 50 minutes, pausing every now and then to ask a question? More likely you spoke for just a few minutes, sketching diagrams and writing a few simple equations. Then you stopped, and asked for some feedback. Maybe you posed a simple question. Perhaps you sketched out a problem for them to try, or asked them to draw a diagram of some sort. Perhaps you asked 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, 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 surely it's ***impractical*** to do this in a room filled with over 100 students – or is it?

My answer is that it is ***not***. It is very possible to recreate in the lecture hall much of the learning environment that exists in the instructor's office. It takes preparation and practice to do it well, but any instructor who is committed to the effort should be able to succeed. In what follows I will explain the approach I have used over the past seven years to try to transform 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.

To begin with, I give up the idea of delivering long lectures. As much as I 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. I was, I felt, presenting these ideas ***as clearly as was humanly possible.*** As long as they were paying close attention, it was simply ***inconceivable*** 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. What I did, any instructor can do – and within 10 minutes, I am sure, the cloud of self-deception will begin to lift from their eyes as it did from mine. Because, you see, 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 they understood my words – but, in fact, they were usually wrong. And here's how I know:

I now am able to 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. (Hopefully, 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; they will have thought it through ***hard*** 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. ***Impossible*** to think that my students could 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 impatiently 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.

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 (2, 3), we have had to construct our own set to meet the needs of a full one-semester course (4). 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 (5).

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 (6), 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 Workbook, which they are required to bring 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 material which heavily emphasizes qualitative understanding, and provides 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.

Among the most dramatic consequences of this instructional method is a very small number of dropouts, typically 1-3% after the first week. End-of-course surveys show that most students react favorably to the instructional methods, with approximately 30-40% giving the maximum rating of 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 positive or neutral, but a persistent core of 10% or less ***despises*** these methods, and the instructor as well (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."*)

What is clear, however, is that the overall learning gains by the students are very high in relation to comparable courses nationwide. For the past six 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 over the past five years are in the 75-79% range, while those of the nationwide sample range from around 43% in the algebra-based course to approximately 51% for students in the calculus-based class (1, 7). Other assessment data are consistent with these results. Moreover, on quantitative problems borrowed from exams given in the calculus-based class, students in my algebra-based course do comparably well, or better.

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.

(1) David E. Meltzer and Kandiah Manivannan, "Transforming the lecture-hall environment: The fully interactive physics lecture," American Journal of Physics **70**, 639-654 (2002); David E. Meltzer and Kandiah Manivannan, "Promoting interactivity in physics lecture classes," The Physics Teacher **34** (2), 72 (1996).

(2) Eric Mazur, *Peer Instruction: A User's Manual* (Prentice Hall, Upper Saddle River, New Jersey, 1997); Catherine H. Crouch and Eric Mazur, "Peer instruction: Ten years of experience and results," American Journal of Physics **69**, 970-977 (2001).

(3) Gregor M. Novak, Evelyn T. Patterson, Andrew D. Gavrin, and Wolfgang Christian, *Just-In-Time Teaching: Blending Active Learning with Web Technology* (Prentice-Hall, Upper Saddle River, New Jersey, 1999).

(4) David E. Meltzer and Kandiah Manivannan, *Workbook for Introductory Physics: Part II* (2000), CD-ROM available from the author.

(5) Lillian C. McDermott and Edward F. Redish, "Resource Letter: PER1: Physics Education Research," American Journal of Physics **67,** 755-767 (1999).

(6) Lillian C. McDermott, Peter S. Shaffer, and the Physics Education Group. *Tutorials in Introductory Physics* (Prentice-Hall, Upper Saddle River, New Jersey, 2002.)

(7) David P. Maloney, Thomas L. O'Kuma, Curtis J. Hieggelke, and Alan Van Heuvelen, "Surveying students' conceptual knowledge of electricity and magnetism," Physics Education Research, American Journal of Physics Supplement **69**, S12-S23 (2001).