

Reference Frame

Reflections on Teaching: Learning from Students

Jerry Gollub

Several recent experiences have provoked me to consider new approaches, even after 30 years of physics teaching. I was stimulated in part by looking at higher education through the eyes of a consumer, my son Aaron, who is now a first-year university student. Although many of us care deeply about our students, it is hard to understand their experiences, because they don't share their concerns very freely (except on the end-of-semester course evaluation). However, Aaron gave me a blow-by-blow description, and I questioned him about what works and what doesn't for him and his classmates.

Aaron is taking organic chemistry, introductory physics, and an interdisciplinary introduction to research in science, all large classes intended for well-prepared freshmen, most of whom have had advanced preparation such as AP courses or research experience and intend to pursue science deeply as undergraduates. What I learned from these conversations may seem familiar, and it certainly reflects a particular set of experiences. On the other hand, our discussions reinforced what I had learned about research on learning, from my participation in studies conducted by the National Research Council (NRC).

To my surprise, I learned that a large introductory science course can be an exciting intellectual experience. As a professor at a liberal arts college that values small classes, I found that news hard to accept. Why do some large courses provide effective learning experiences, while others do not? Aaron explained, "In Organic, we were constantly asked, 'How do you

know that this is true?' We had to build up our knowledge of science from scratch, to be critical instead of just accepting what the professor or great scientists had said. On the other hand, in Physics, the professor was a fine lecturer, but we never talked about how physicists actually figured out the equations that described nature and what the important experiments were. It didn't seem like science, just applied mathematics." Aaron's comment reminded me that learning involves building an effective conceptual framework that can be used to organize diverse phenomena.¹ When we help students to share in the act of discovery and to argue about ideas, they are more motivated.

Peer interactions

The frequency of productive interactions between students was better in the course that emphasized critical thinking. "It felt like we were being thrown into a jungle, with high expectations. To stay afloat, we had to work together and get each other's inputs." Many studies have shown that learning can be facilitated by peer interactions in which students support classmates' efforts to master difficult material.² I was surprised to realize that student interactions can overcome negative factors such as large class size or the difficulty of the subject. There are many ways to nurture student interactions, such as setting up study groups or taking time for small-group or pairwise discussions during class, as Eric Mazur³ and others have advocated. Each of us can find a different approach to encourage peer interactions once we recognize how important they are.

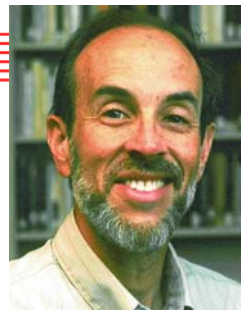
Many of us are afraid to encourage group study; we fear that weak students may become dependent. However, one can monitor participation to encourage equitable sharing—for example, by rotating responsibilities so that everyone presents ideas. Many students say that solitary problem-

solving is a turn-off, and it may be one reason we lose so many students to other fields. However, students will not easily form supportive study groups unless we encourage and facilitate them. According to Aaron, "In Physics, the problems were boring but manageable, so there was no real incentive to work together. The good students could do them on their own."

Conversations with Aaron also suggested that most instructors misjudge the extent of experience and practice needed to master basic physical principles. "Problem sets were often plug and chug, or variations on examples in the book." Typical assignments, even more challenging ones, don't provide enough practice to master the ideas, because each problem involves a little thinking and a lot of calculating. That is why students typically report, after a disappointing performance on an exam, "The questions were quite different from those assigned as homework," even though to a physicist, both involve the same principles. More varied assignments can help students to master key ideas. Such assignments might include designing strategies to solve problems (but not always solving them), doing and reflecting on simple home experiments, answering conceptual questions of the kind that are now included in many textbooks, and inventing questions designed to elucidate important principles.

Making connections

Traditional subjects, including physics and chemistry, need enrichment through interdisciplinary or applied connections. The chemistry course that Aaron found exciting made quite a few connections to other fields; the explanations of chemical bonding were based on quantum physics, for example. Physics courses might explain why we see only one side of the Moon, why mechanical systems are not always predictable, or how energy concepts can help us understand chemical reactivity.



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Making applied and interdisciplinary connections can help overcome a serious motivational problem. Students who have seen the main ideas of physics in an AP course, or who have been exposed to molecular biology, often find physics excruciatingly familiar, even if they have not mastered it. While some contemporary courses demonstrate the power of physics to explain diverse phenomena, most physics courses could do it better. I try to make connections in my own teaching, by using chemical examples when discussing statistical mechanics and by explaining how organisms use fluid mechanics principles to survive. The connection strategy may also facilitate learning, because much research¹ shows that applying learning to new situations is difficult.

Reasoning and concept mastery

Aaron reminded me of the importance of balancing conceptual learning and mathematical reasoning in physics teaching, as those who are active in physics education research have emphasized. Seeing a principle derived does not generally lead to deep understanding without a major effort to elucidate the degree of generality, the underlying context, the meanings of the symbols, and so on. Yet if you look at students' class notes, you see only equations with little interpretation.

I am not suggesting that we pull rabbits out of hats, but mathematical reasoning alone cannot be expected to be our primary teaching tool, and it doesn't appeal to more than a modest fraction of our students. After all, less than 10% of students in our introductory courses are likely to major in physics. Many cite mathematical difficulty as a reason for dropping out of physics, including some who do well in mathematics courses. Mathematical reasoning alone may not help many students to develop confidence in their ability, a prerequisite to learning and persistence. More advanced courses offer an appropriate opportunity for mathematical focus.

How can we improve the impact of physics teaching on reasoning skills and concept mastery? Most courses are defined as sequences of content topics to be mastered. Instead, one can decide what students should be able to do at the end of a course, and then select suitable content to foster those capabilities, as I learned at a recent workshop on course design run by Barbara Tewksbury, a geologist at Hamilton College. Doing so is somewhat laborious and requires self-conscious analysis of each educational de-

cision. Designing courses to teach specific capabilities seems particularly suitable for topical courses for nonmajors, where we have freedom to design a course from scratch. Next time, I plan to select goals up front (for instance, "Students should be able to recognize and use basic conservation laws in reasoning about everyday situations involving fluid flow"), and then consider how particular examples can help achieve those goals.

Coping with heterogeneity

The importance of variations in student preparation and expectations was brought home to me when I taught a course called "Fluids in Nature" for nonmajors; it dealt with natural phenomena, biological and physical, that involve fluid flows. We considered how organisms use their fluid environment to swim or fly and to exchange matter and energy. We also considered basic atmospheric issues, such as why the atmosphere is cold at high altitudes, what determines the mean temperature of Earth, and why rainfall often accompanies low atmospheric pressure. (In such a course, basic ideas such as pressure and thermal energy have to be taught along the way.)

A graphic example of the effects of student diversity came from two students in the course evaluation. One wrote, "The course provided an experience sufficiently good to give me scientific insight into the world. . . . More importantly, it rekindled my interest in mathematics and science." However, another student said, "The unexpected difficulty of the course due to an unknown assumed level of scientific knowledge by the professor at times counteracted its ability to be interesting." The two students had divergent reactions to the same educational experience. What might I have done to detect and solve this problem well before the end of the semester?

Getting early and frequent reactions from students is critical, whether by using personal electronic response systems (now widely available commercially) or by obtaining written or oral feedback during class. This basic principle is a key element in research on educational assessment.¹ Long before students take an exam, the instructor needs to know (at least statistically) what they are learning, what they already know, and what they think would make a course more effective. Getting information quickly is critical in coping with the inevitable diversity of students' prior experience.

New options, simple rules

Just as students are diverse, so are instructors. But the resemblance among the dominant textbook choices, along with the natural inclination to follow a text closely, tends to make courses look almost the same. How can we take advantage of the potential excitement of learning physics from gifted and committed teacher-researchers who have something original to say? It is hard to teach without a textbook, but one possibility is to consider an unconventional text that takes a different point of view.⁴ Another is to seek out and use supplemental Web-based instructional materials that reflect our own choices about what is important, or that help particular groups of students. We have many more choices about how to structure courses at all levels than we did a decade ago, better supporting materials, and more information from research on learning about what works. So we ought to be able to do a better job for our students.

In summary, I advocate these simple rules: Engage students in arguing about ideas, facilitate peer interactions, diversify the types of practice and experiences that are included in assignments, connect physics to applications and other scientific disciplines, balance mathematical and conceptual reasoning, design courses with outcomes in mind, and take care to learn from students through early and frequent feedback.

I appreciate helpful comments by Peter Collings, David Hammer, and Aaron Nissen.

References

1. A useful summary of the literature on learning may be found in the National Research Council report *How People Learn: Brain, Mind, Experience, and School*, National Academies Press, Washington, DC (2000). <http://books.nap.edu/catalog/9853.html>
2. For a summary of research on peer interactions at various educational levels, see *Learning and Understanding: Improving Advanced Study of Mathematics and Science in U.S. High Schools*, National Academies Press, Washington, DC (2002). <http://books.nap.edu/catalog/10129.html>
3. The effective use of peer interactions in physics lecture classes is documented in E. Mazur, *Peer Instruction: A User's Manual*, Prentice Hall (1997).
4. For an example of an unconventional introductory text that explores the mechanical and electrical properties of real substances, see R. W. Chabay, B. A. Sherwood, *Matter and Interactions*, vols. I and II, Wiley (2002). ■