Physics for the Non-Scientist: A Middle Way

Michael Sobel, Brooklyn College, Brooklyn, NY

Recently a comedian in a comedy club in New York asked me if I was a professor. I said, "Yes, a professor of physics." "Physics!" he said. "I was in a bookstore and saw a book, *Physics for Dummies*. I opened it and it said, 'You'd better cheat.'" Physics has that reputation, as all of us in the field know, and yet I'm not sure if we have grappled with the reason why.

Conceptual Physics

Chemistry is hard, and math is hard, but physics is in a different category, and as result we have over the years had very few students taking a traditional physics course, other than a certain sort of very bright student and those required to take physics to enter some other field (engineering, medicine, etc.). In particular, the science distribution course—the requirement that the majority of colleges impose on liberal arts majors—is very unlikely to be "Physics 1 and 2," whether it be the algebra-based or the calculus-based course.

But these days, physics educators have reason to be pleased. Enrollment in physics is on the rise both in high schools and colleges, and the explanation is clear: We have a new kind of physics course, most often called "conceptual," that is being used to reach out to a broad audience of America's young people, without the agonizing problem solving and math.[1] (Conceptual courses have of course been around for a long time, but now they are being offered and taken more widely. One expects they will impact the way physics is thought of among the public.)

This development surely enhances the budgets of physics departments and the job prospects of physicists, but I think it is appropriate to question whether it is in the best interests of society and the goal of scientific literacy. My object in this paper is to suggest a middle way between the traditional physics course and the conceptual course that, certainly not overnight but perhaps in the long run, might better serve the deeper interests of the populace and allow us to better meet our responsibilities as scientists and educators.

Originality

Why is physics so difficult? One reason must be that we go too fast, as has been discussed in a number of places; we add to the curriculum as the 20th century gives way to the 21st, and we cannot take away the 17th century. This flaw in the physics program is easily remedied in principle, although not in practice. Indeed, textbook publishers seem wedded to continual growth. But there is another factor that makes physics hard, more inherent in our understanding of our field, and that is the demand we make that our students solve problems that are, in some sense, original. Although we may spend time in class on derivations and demonstrations, the students all know that, come exam time, they will have to solve problems. And the problems will not be simple plug-ins; in fact they will not necessarily be problems they have practiced on for homework. Moreover, students know that sitting in the classroom and absorbing everything the professor says will not get them very far—or at least not far enough. They've got to do enough problems as homework so they infer general strategies and then employ the strategies on new problems on the test. We tell them they've got to "do" physics. (One of my colleagues uses the analogy of the piano player: You can't learn to play by watching a great pianist play.)

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Physics and Mathematics

All this makes sense for the students preparing to be scientists or engineers, who, in their careers, will have to use their wits to solve problems not quite like the ones they solved before. But it doesn't make sense for students majoring in another field. It doesn't make sense for two reasons: One, they are not likely to face this kind of problem-solving challenge in their future. And two, they are not likely to succeed in this kind of physics course at all. So for the nonscience student we ought to do something else. But what? Does it follow that we have to offer a course that has no mathematics at all, or that has only mathematics to look at, not math for the student to do? In the words of Paul Hewitt, author of *Conceptual Physics* and other books, "(t)o the nonscience student, physics is enormously interesting ... but when paired with problem solving, the price of admission is too high for too many."[2]

There are two responses that the physics educator might make to the rise of conceptual physics: One, physics is inherently mathematical. (Indeed other sciences are mathematical too, to a greater degree than a generation ago.) The Sun is a star and it only appears so much brighter because it is nearer. That's a fine argument for an eight-year-old child. How much more convincing and satisfying it is to know that the inverse-square law for light shows that the intrinsic brightness of the Sun is similar to that of near stars. That's reasoning for an educated adult. And does the student really know what gravity is about when told that the Sun's gravity makes the Earth move in its orbit? Or does he/she have to comprehend the concept and the *quantitative* nature of centripetal acceleration, plus the nature of the inverse square force, plus the combination of these ideas leading to Kepler's third law in order to see how the physics of Newton explained the solar system?

I use this last example deliberately, recognizing that it represents one of the hardest sequences in the first semester of physics, knowing that even students who do well in a traditional physics course may not really grasp the whole derivation or have a feeling for the motion. Yet I am convinced that the very nature of the "scientific revolution" (as historians call the age of Galileo and Newton) eludes the student who has not ploughed through these equations, that, indeed, Newton would not have become the superstar of the 17th century if he had not explained the motions of the Moon and the planets.

Physics is mathematical not only in the sense that algebraic and geometric analyses have to be carried out in order to follow its logic, but also in the sense that numbers alone are important. It is a truly awe-inspiring accomplishment for scientists to have deduced that the mass of the Sun is 2×10^{30} kg and that there are 6×10^{24} molecules in a cup of water, numbers so far beyond what we can count. Physicists are so experienced dealing with these things that we tend to forget how awesome it is (to use a word that students will relate to), but it is only truly awesome if the student sees how the number has been discovered.

The second response of the physics educator to the idea of "conceptual physics" should be, "Why *can't* they do the math?" Why can't students who have studied mathematics for, say, 11 years be expected to follow an analysis, based on geometry and algebra, laid out carefully for them? I do not mean to suggest, naively, that the average nonscience students in college today can handle the quantitative work in a traditional physics course just because I say they ought to. But I do suggest that it is the responsibility of the physics community to insist that something is seriously wrong with an education program in which the efforts of students and teachers over so many years is almost completely a waste. We've all spoken to the student who says, "I did very well in algebra, except for the word problems." For us, the word problems are everything. I also suggest that after so many years (decades) of failure, math education ought not to be left to the mathematicians, that physicists (also other scientists) must demand a place at the table preparing math programs for the schools. Perhaps the key to math education is to tie it to physics and other science applications at all points from elementary through high school. Perhaps at some future time, students will study math to the same level as today but will remember and know how to use it.

A Middle Way

But, to return to the present, how might a physics course be designed that avoids the shallowness of conceptual physics yet lies within the capability of the *average* student today? I propose that we design a course that does what most other college courses do, a course that asks students to learn what the teacher does in class, and what the teacher assigns in the text, but nothing more. It will be a course that does not demand ingenuity, that does not demand that the student put together two ideas that he/she has previously used separately, that does not demand that the student be clever. The student sees a certain problem done in class, then tries three or four examples of the same problem with different numbers at home, and later has to do one on the exam. For a given subject or chapter, there might be four or five such problems, starting with a simple plug-in followed by more complicated examples. To what level of difficulty might one go in selecting problems? That would have to be evaluated by trial and error, but many of the middle-level problems found in a typical textbook today would probably be excluded.

Let me illustrate with the subject of uniform circular motion. The first problem might be one in which a single force keeps a body in motion—say, a mass on a string moving in a horizontal circle on a frictionless table; the student is asked to find the tension in the string given the radius and velocity. In a second type of problem, the velocity, period, radius, and force are all possible unknowns. In a third type of problem, the centripetal acceleration is v^2/r, but there are two forces —say, a mass moving in a vertical circle with both weight and tension contributing to the centripetal force. Another type of problem, say, the three-dimensional case in which the mass moves in a horizontal circle at the end of a string and the string dips at a certain angle below the horizontal, might be too difficult. The physics instructor does not feel obliged to assign the problem because it is "fun," or challenging, or "technically sweet."

In other words, such a course is doable for average students because they are not expected to figure out for themselves how to work the problem, how to convert from the words to the equation, how to go from the diagram to the vector components, etc. They are taught that and study it before the exam.

Similarly, in dealing with large numbers, although one cannot ignore the fact that many nonscience students in the average range don't remember (even though they probably learned it once) how to use numbers expressed in scientific notation, they can relearn it. Some preparation and practice would be provided early in the term, possibly on a self-teaching web page.[3] Various key calculations (the mass of the Earth, the size of a molecule, etc.) would be carried out by the instructor. The students would repeat these, do some similar calculations themselves, and then demonstrate this capability on an exam.

Questions

A course like the one I advocate may be called "rote learning" and criticized as such. I would offer a number of responses:

1. Rote learning is following a procedure without understanding it. That's not what I propose. Being taught how to do something by a teacher or a text does not imply a lack of understanding, and there is no reason to think that teachers of physics are any less capable of teaching with understanding than teachers of any other subject. To be honest, however, as in all studies, some students will learn some material by rote.
2. But rote learning is not a total loss. Often material learned by rote shifts into understanding after the passage of time and study, especially in a spiral program.
3. The conceptual physics course, without the backing of quantitative analysis that underlies our professional understanding of our subject, is much *more* likely to be a series of memorized facts, learned by rote, than a course with a quantitative basis.

Many in the physics education community will be aware of the insights gained in physics education research in recent years.[4] In particular, it has been learned that a mastery of problem solving, of the kind traditionally central to physics courses, does not necessarily lead to an understanding of physics concepts. Nevertheless, few physicists would advocate abandonment of problem solving in the traditional introductory course, and I propose that it ought to play a role in teaching nonscientists also. This does not preclude attention to newer research-validated methods for increasing conceptual understanding.[5]

Content

This course for the nonscientist would have to be more leisurely, with more time being spent on each subject than in the traditional course—for example, two weeks or more on circular motion, two weeks on two-dimensional projectile motion, and so forth. Some of the subjects usually taught in introductory physics would be eliminated. One criterion for elimination could be whether subjects relate significantly to subjects elsewhere in the course. Candidates for deletion might include the properties of liquids, electric currents, and sound.[6]

More fundamentally, subjects that would be chosen would form part of a coherent story that develops over several weeks in the course. One such story would be the argument from the law of inertia, through universal gravitation, to the motions in the solar system (and Kepler's laws). Another such story (as I have discussed elsewhere[7]) might be the kinetic theory of gases and its success in simultaneously explaining pressure and specific heat, thus supporting the molecular hypothesis. The course would be developed, not as a series of 25 or 30 chapters over a year, but as seven or eight major stories encompassing all of the essential general principles of physics, but not all of physics.

Finally there is the matter of derivations. It always seemed anomalous and inconsistent to me that I would spend a good deal of lecture time (in traditional introductory physics) showing students how important principles of physics follow from Newton's laws (say, momentum conservation or the pressure of a gas), yet these arguments would not be on the exams. Exams would consist solely of problems, and students would know that and feel free to not pay too much attention to what I was stressing in class. In later years I did include, within limits, some derivations on exams.[8] I would argue that also in core physics for the nonscientist, derivations embody the logic of what physics is about, and should be part of what students are taught and what they reproduce.

Conclusion

To summarize, the physics-for-nonscientists course must be much less encyclopedic than the traditional physics course. One wants in a semester three or four sequences, or "stories," each showing how a combination of experiment, analysis, and calculation leads to a deep understanding of an important aspect of the physical world. The story is presented in the lecture and the text, and the student learns the presentation, much as the student learns the story of the Civil War in a history course. The students don't stop there since the discoveries of physics, unlike history, are largely in the form of equations. They see that equations can be used to answer questions (will the baseball go over the fence?), learning thereby that equations are much more than scratches on a page. To do this they don't have to be clever; they just have to be industrious.

References

1. Toni Feder, "More physics in U.S. high schools," *Phys. Today* **60**, 32 (March 2007). Data on introductory college physics are included in the graph.
2. Paul G. Hewitt, *Conceptual Physics,* 9th ed (Pearson, Addison-Wesley, 2002), p. xx.
3. In two different courses for education majors taught some years ago, I asked students to study some notes on operations with scientific notation, including illustrative and assigned problems. They learned, largely on their own, to use these techniques quite successfully.
4. L.C. McDermott and E.F. Redish, "Resource Letter: PER-1: Physics Education Research," *Am. J. Phys*. **67**, 755–756 (Sept. 1999).
5. See, for example, L.C. McDermott and the Physics Education Research Group at the University of Washington, *Physics by Inquiry,* Vols. I and II (Wiley, 1995).
6. "Conceptual Physics" as a course for nonscientists is in danger of becoming standardized (fossilized?), just as happened with "Physics 1 and 2" some (perhaps) 75 years ago. In a way my writing this article is an attempt to forestall this standardization and to create some space for discussion. But there are *two* issues about the course that ought to be debated: (1) How to teach, and (2) what to teach. This article is about (1); the paragraph here footnoted is a stand-in for (2).
7. Michael Sobel, "Teaching thermodynamics and the nature of matter," *Phys. Teach*. **45,** 511–515 (Nov. 2007).
8. It seemed it would add excessively to the students' burden to ask them to memorize all the analysis in, say, four or five chapters of the textbook for an hour exam. Instead, I told them that prior to the exam I would select three or four specific derivations, of which one would be on the exam. This way they had to pay attention to what I was doing.

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Michael Sobel *is a professor in the Physics Department at Brooklyn College and in the doctoral program in physics at the CUNY Graduate Center. His interests include theoretical nuclear physics, statistical mechanics, societal aspects of science, physics for a nonscience audience, and teacher preparation. He is also on the doctoral faculty in Urban Education at the Graduate Center.*

Brooklyn College, Physics Department, Brooklyn, NY; MSobel@brooklyn.cuny.edu

• **Editor's Note:** In next month's issue, we will be publishing a response paper by three authors who hold a different view.