Moving the mountain: impediments to change

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There is no doubt that since the beginning of this century the United States ranks first in generating outstanding scientists. It is therefore ironic that, as a whole, the population of the United States scores low in Science and Mathematics. One only need turn to the media to see that our society does not value science and science education as it did just a few decades ago. In spite of all the advances in science and the many contributions of related technological developments to society, science illiteracy is rampant. The average person has little faith in scientists, and more pressing problems than science education are on the agenda of most people. These developments are worrisome because for everyone to understand at least what science is about is in the interest of society. No one can deny the formidable advances that have been achieved in science and their impact on the quality of life — advances that would not have been made without the outstanding quality of American scientists. What happens now in the classrooms across the United States will directly affect the health and well-being of this country in the next century. We must act now to prevent losing our edge in science and technology.

At the college level, the introductory science course often is one of the biggest hurdles in the academic career of a student. For a sizable number of students the course leaves a permanent sense of frustration. [1] I only have to tell people I am a physicist to hear grumbling about high school or college physics — almost to the point of making me feel embarrassed about being a physicist. This general sense of frustration with introductory science is widespread among non-science majors required to take science courses. Even science majors are frequently dissatisfied with their introductory courses, and a large fraction of students initially interested in science end up majoring in a different field. What have we done to make it that way, and can we do something about it?

Science education has been focused much too long on competitively generating a steady supply of future scientists. We must direct our science education not just at students going on to a scientific career but also at those majoring in other fields. It is time to realize that the demand for scientists is determined to a large extent by people for whom the introductory science course is the only direct exposure to science and who remember science only by the frustration it has caused them. It is time to realize that those who become successful scientists do so in spite of the current educational system, not because of it. It is time to realize that better science education for all will ultimately lead to a higher quality of life.

Broadening and improving science education will require a major change in attitude. The current mode of instruction is self-perpetuating: postsecondary faculty educate both their own successors and future secondary teachers; secondary teachers, in turn, prepare the next generation for a new cycle. At all levels one can find excellent teachers, but for the most part instruction in science is geared toward the scientist, not the general public.

The first step in remedying this problem is to create awareness: few faculty have a good understanding for what their students are actually learning in, let alone retaining from, their science courses. I, for one, had gone on lecturing happily for many years before realizing that students were not at all learning what I wanted them to learn [2]. Students were memorizing by rote and learning to *cope*. My goal was to teach them physics; their goal was to get a good grade. How can one reconcile these two? An obvious answer is to make sure that the assessment — examinations, homework assignments, etc.; all that enters into the final grade — properly reflects the goals of the course. Herein lies precisely the problem: the standard assessment is often a false indicator. Students often manage to score perfectly on standard problems without understanding any of the underlying basics. [2–3] They have learned to solve problems mechanically, by memory or by analogy. A recent retention study carried out at Carnegie Mellon has shown that two years after completion of a traditionally taught introductory course, students' knowledge of the material is back to where it was *before* they took the course — the only things that remain of the course, of the students' and the instructor's efforts, are the final grade and memories that, in all likelihood, are not among the most pleasant ones. Clearly, before we can even begin to remedy any problems in education we must create a broader awareness of these problems.

One way to create broader awareness is to create assessment instruments that uncover failures in our current educational system. In my own field there currently is an abundance of such instruments, all of which focus on assessing students' understanding of important basic concepts. [4] Still, by themselves, these instruments are not sufficient. It is all too easy for a skeptical instructor (of whom there are many) to dismiss the instrument as faulty — in other words to blame the test, and perhaps the students, instead of the method of instruction for any poor results.

What convinced me — and I count myself among the skeptics — is so-called *paired-problem* testing. Instead of focusing on just the underlying concepts, I began to ask for every topic taught in my course a combination of two types of questions: one conceptual, the other traditional. The juxtaposition of these two types of problems is illuminating: what struck me when I began this *paired-problem* testing a few years ago was the enormous contrast in performance. My students did very well on the traditional problem, but poorly on what I considered to be a very simple qualitative problem *dealing with exactly the same basic concepts*. For the first time it became clear to me that students often simply recognized a traditional problem as one that pertained to a certain formula, in which case all they needed to do was to put the right numbers in the right place and work through the algebra — about the only thing necessary to solve the problem was the classification of the problem, the recognition of the correct equation or procedure. At the same time, their poor performance on the "simple" qualitative question was a clear indicator that the students had no clue what the equations or procedures they were using really meant. And, naturally, a few months after completion of the course recollection of the equations and procedures fades away, leaving little substance behind. The point I want to make here is that it is not sufficient to devise new assessment methods. A side-by-side comparison of students' performance on qualitative questions and on more traditional quantitative questions is a crucial element in uncovering the shortcomings of the traditional method of instruction and convincing faculty of the need to change.

Once awareness is created, the next step is to devise an instructional method that effectively addresses the shortcomings of the traditional method. I will not dwell on this topic, however, as my co-panelists have extensively addressed this problem, and I have recently written on this subject [3]. Let me simply add that, with support from the National Science Foundation, I have begun setting up a web site aimed specifically at disseminating successful and simple-to-implement instructional practices. [5]

A final point I wish to address in this paper is what I believe to be an important impediment to change. Failure to recognize this barrier seriously compromises our efforts. Put simply, the problem is the following: the initial effect of any change is not an improvement, but a period of problems, adjustments, mismatch, and to some extent a period of frustration and pain. A good analogy [6] is that of a tennis coach who discovers that one of her students is not holding his racket correctly. After adopting the correct grip, the student's performance does not immediately improve — in fact, it gets *worse*: most balls go into the net or off to another court. The student gets frustrated because he is used to holding his racket differently and, it now appears, played *better* the old way. The coach, however, knows that the student can never improve without the correct grip and that her student's play will soon improve.

An instructor of a large introductory class is likely to think differently when facing the often intimidating discontent of his audience. "Am I doing something *wrong*?" or "This is not working!" are natural reactions. After I changed my method of instruction, a student once asked me: "Professor Mazur, when are we going to do some *real* physics?" Others, having done well in their high-school physics class, are very disgruntled when they discover that their high-school performance does not translate into a good performance in my class — they blame their performance on this so-called improved method of instruction forced upon them by me. Expecting immediate improvement is not only naive, but is bound to lead to disappointment. It is therefore important to make instructors who are embarking on a new road aware of this obstacle. In addition, it is important to prepare the students for this transition.

An additional problem is that the keeping of statistics and the desire to maintain a "fair" and consistent grading system from one year to the next tend to perpetuate the status quo. An administrator once told me: "Your method does not work because our good students no longer do well — look, there is very poor correlation between your results and our statistical analysis of course performance over the past ten years!" "Good" here means "good by the traditional standard," and this is the essence of the problem: changing the method of instruction also means changing the method of assessment. How else can one assess the success of the change and, what is perhaps even more important, drive students to change? Changing the method of assessment, however, means giving up any meaningful correlation with previous assessments. As long as administrators and faculty do not realize that this poor correlation is an unavoidable consequence of change, it will be impossible to move forward.

Notes

[1] Sheila Tobias, *They're Not Dumb, They're Different: Stalking the Second Tier* (Research Corporation, Tucson, AZ, 1990).

[2] Lillian McDermott, *How we teach and how students learn — A mismatch?*, Am. J. Phys. 60, 295 (1993).

[3] Eric Mazur, *Peer Instruction: A User's Manual* (Prentice Hall, Upper Saddle River, NJ, 1997).

[4] An excellent example is the *Force Concept Inventory* by I. Halloun and D. Hestenes; see [3] for the most recent version of this test and other assessment instruments.

[5] This web site can be reached via the URL http://galileo.harvard.edu.

[6] This wonderful analogy was pointed out to me by Phil Sadler of Harvard University, who recently studied student performance and grade correlations in classes using novel approaches to teaching.