have done science in college. But, except for some pressure from ROTC during his senior year in high school, Eric was not recruited to science either in college or before. Nor, despite his high school background, was he emboldened to try science as an elective. Eric had other options and developed "other loves" in college. Since he never appeared in a science course, no one in science ever got to know him (any more than he got to know them). As a result, there was no one, neither awesome professor nor friendly science teaching assistant nor science-trained college counselor available to him when, in the middle of his undergraduate career as an English major, he felt the need for more rigorous study outside of English. Observing that it was the treatment of *ideas* in literature and, especially in literary criticism, that attracted him to English more than the sheer aesthetic pleasures of poetry and fiction, Eric at one point considered a shift into philosophy. But he found philosophy, as currently practiced, narrower still, and so he stayed in English. Until recruited for this project, Eric never reconsidered science as a course of study or as a career. His journal and his postcourse reflections on the experience of taking college physics last summer give us insight into why.

Professional scientists may be tempted to dismiss comments and criticisms from second tier stand-ins as but further "proof" that they are not "one of us." But that would be missing the point. If the sciences are to attract any new group of students to science, either to meet the projected shortfall or to solve the science illiteracy problem, the effort must begin by getting to know some of "them," and well.

ED21 Tobias, S. (1990) They're not dumb, they're different, stalking the second tier. Research Corporation.

Introductory Physics: The Eric "Experiment"

"The notion of a 'calling' is deeply ingrained in the mythology and history of science. If we assume that all students are 'called' in the same way and by the same age, we fix what is inherently variable— the size and composition of the talent pool."

—Daryl Chubin[1]

Eric found it "strange" to be in class again, especially in a lecture class where "everyone looks tired" and no one seemed particularly excited by the prospect of the five-week introductory physics course that lay ahead. His fellow classmates, as he perceived them, were either "bored" or "scared," he noted on the first page of the daily journal he was keeping of his reactions as a literature student to introductory physics. In even the most obscure literature class, he wrote, "there are always people who are intensely interested, at least at the outset. Is it simply the nature of the subject that makes elementary science classes appear unexciting, or is it the teaching style?"[2] Part of his assignment, as a participant-observer for a project supported by Research Corporation, was to find out.

Because it was a summer session, Eric would not experience the anonymity of the larger classes that characterize introductory physics. He shared his course with only 30 others, 20 men and ten women (not the gender balance he was used to, as he recorded in his journal). But the habit of teaching large classes and the demands of the fast-paced summer-school schedule prevented his instructor from modifying the lecture format. One look at the assignment sheets and at the weight of the text[3] gave Eric some sense of the amount of material to be covered, and some anxiety. To add to his travail, he discovered his calculator wouldn't handle exponents when he began to work the problems that first evening (he borrowed an HP 15-C the next day). More serious was his worry that, although he had taken college calculus (a condition of his assignment as participant observer in this course), his brain

[1] Daryl Chubin of the Office of Technology Assessment, U.S. Congress, made these remarks during a talk at the AAAS National Meeting, New Orleans, Feb. 17, 1990. Quoted with his permission.

[2] Eric, of course, was not around after class when the few students who were intensely interested in the subject went up to speak to the instructor.

[3] Halliday and Resnick, *Fundamentals of Physics*, Third Edition. New York: John Wiley, 1988.

wouldn't handle the computations. And it was clear there would be no respite either from the pace or the expectations. "The instructor gave the class the impression," Eric noted on the first day, "that since *he* had had to make it through the 'elementary grind,' so must we."[4] Literary studies offer a different kind of challenge, Eric noted right away. "In literature," he wrote, "the cutting edge is accessible, even if it is unlikely to be mastered by a beginner. In physics, a correct solution may be harder to figure out, but once done it will be indistinguishable from the professor's own." This insight soon became palpable for Eric when he discovered the "one nice thing" about physics: "as I try and endure, the understanding comes. And this does not necessarily happen in the humanities."

On the second day Eric began to notice more profound differences between the "values," as he put it, of a person in the humanities and those of a scientist.

> In a discussion of one of the homework problems, we were to judge the best clock for timekeeping, given a record of five clocks' readings at exactly noon. The professor chose the clock that gained exactly 51 seconds every day. I picked the clock that was within seven seconds of noon, day after day. A scientist wants predictability. I would rather have convenience.[5]

But the first "real day" of lecture disappointed him.

> The class consisted basically of problem solving and not of any interesting or inspiring exchange of ideas. The professor spent the first 15 minutes defining terms and apparently that was all the new information we were going to get on kinematics. Then he spent 50 minutes doing problems from chapter 1. He was not particularly good at explaining why he did what he did to solve the problems, nor did he have any real patience for people who wanted explanations.

Eric was learning that, for the most part, "why" questions are neither asked nor answered. The preference is for "how" questions. Perhaps because of this, his initial assessment of the teaching mode (compared to what he was used to) was negative.

> I do not feel that what this professor is doing can be considered teaching in any complex or complete sense. My understanding is that we are to learn primarily by reading the text, secondarily by doing problems on our own and comparing our solutions to those on sale in the physics office, and thirdly by mimicking the professor's problem-solving examples. Simply by intuition, I know physics, and more generally science, to involve creativity and finesse; but this man makes it into a craft, like cooking, where if someone follows the recipe, he or she will do well.

There was, indeed, a discrepancy between Eric's expectations and those of his professor (note 4).

By the end of the first week, classes seemed a little better or maybe, as Eric wondered, he was just getting "used to the way [the course] is being 'taught.'" Still, he felt patronized by the teaching style.

> I still get the feeling that unlike a humanities course, here the professor is the keeper of the information, the one who knows all the answers. This does little to propagate discussion or dissent. The professor does examples the "right way" and we are to mimic this as accurately as possible. Our opinions are not valued, especially since there is only one right answer, and at this level, usually only one [right] way to get it.

It was not the physics that bothered him. In later segments of his journal he would praise the text, a book borrowed from the physics undergraduate office that he begged to be able to keep when the course was over. He found his old love of math coming back. In the quiet of the university library where he spent afternoons trying to work the problems, he was "really quite content," he wrote. It was the class that bothered him most at the beginning, but he was honest enough to realize that as he "got more into the physics," he liked it better.

> As I am able to ask more knowledgeable questions, class becomes more interesting. I am finding that while the professor is happy to do example problems for the entire period, he will discuss the real world ramifications of a theory if asked.

His classmates didn't appreciate his interruptions, however. They seemed to "lose patience" with his "silly 'why' questions." These got in the way of the mechanics of finding the right solution to their assigned problems. And this was what, as Eric perceived it, physics was all about—for them.

He was finding more differences between doing physics and doing literary analysis. The professor's suggestion that setting up the problem and understanding concepts is more important than doing the arithmetic reduced Eric's homework time from six hours per night to three. He was happy to be relieved of some of the computation, but bothered, too. "Imagine being asked to show only that you *could* write a paper on the use of gender in *Tom Sawyer* without having actually to do so," he wrote in his journal that night.

[4] The instructor, reading these comments, did not recall ever using the term "elementary grind," but agreed that he brought to his teaching certain prejudices about who takes summer school physics and why: he assumed his students were "preprofessionals who have already decided on a career in science and are in class to learn problem solving." After reading these comments, he conceded he needed to be "more guarded about what I say..." and that "extreme care must be taken to set a good mood for the course, and to offset the prejudices students bring with them."

[5] Page 11 in the text, question 30P.

Two weeks into the course, Eric was becoming skeptical about some of the models. His attention to language and his continuing need for answers to "why" questions was decidedly getting in his way. His July 9 entry reads:

> OK, I might as well admit it now. I don't really believe Newtonian mechanics. It works, yet somehow I think there are various forces which are made up—not really understood—just to make the calculations work out. Is there really a normal force?[6] The force which pushes a book down on a table is gravity. Yet the "normal" force which comprises the table pushing back on the book, seems a little strange. Why should a table push on a book? Maybe it should be called the "abnormal" force? And action-reaction seems to me to be a misnomer..."Action-reaction" presupposes a cause and effect relationship which implies duration, but in physics the "action-reaction" happens simultaneously.[7]

By then he was starting to look around a bit more at the students in the class. Everyone looked clean cut and serious, he noted. Yet, there were a few people who caught his eye.

> There is one man with a crew cut who always sits in the front row and always wears a hat that says, "Life is too short to dance with ugly women." Another extremely muscular "frat boy type" catches my attention only because he always mutters the right answer several seconds before anyone else. I have decided he is either a genius or he has taken the course a few times before. There is a Hispanic woman who sits next to me who is already having trouble with the material. She tells me she spends seven hours a night on homework and needs to get an "A" to receive an ROTC scholarship for next year. A pretty blonde premed sits behind me. She acts like she wants to be friends, but her conversations always eventually turn to, "...By the way, what did you get on problem 57?"

Yet, even though the class was small, there was "no sense of community within the class," Eric noted, a fact he would later comment on at length. He attributed this to the lecture format and to the subject, devoid, as he put it, of "personal expression."

[6] Eric knew full well by then that the normal force in physics is the force perpendicular to the contact surface. He was playing with language.

[7] According to Arnold Arons, professor emeritus of physics, University of Washington, Eric's question concerning time intervals elapsing in connection with force adjustments having to do with Newton's third law, "is one of the deepest questions arising in classical physics. The question must be planted deliberately, and students must be led to think about and discuss it. There are very very few Erics who raise it spontaneously." (Personal communication to the author.)

> Nobody seems particularly interested in making friends or seeing each other outside of class. This may be one reason people dislike math and science classes, their lack of community.

The first exam gave Eric some important insights both into how physics is taught and why the sense of community was so lacking. He personally found the exam "easy," easier than the homework which, as he expressed it, "involved the use of multiple concepts and numerical manipulations." In contrast, he wrote in his journal, "the exam problems asked only for a simple exhibition of skills acquired." He was "frustrated" to have spent so much time on problems which he would not encounter on tests. Later he concluded that the homework problems were really too hard, "discouraging rather than encouraging. Sometimes you are asked to display a knowledge of so many concepts at once, it is hard to get a hold of things."

But the real impact of the exam was felt when the exams were returned to the class.

> When we got our exams back this week, everyone was concerned about how other people scored. I understand that natural curiosity and in my literature classes there was always some comparing done between friends. However, I've never experienced the intense questioning that has happened this week. Almost everyone I talk to at some point or another asks me about my grade. When I respond I scored an "A,"[8] I get hostile and sometimes panicked looks. It is not until I explain that I'm only auditing and that my score certainly will not be figured into the curve, that these timid interrogators relax.

There was, in fact, no "grading on a curve" in Eric's course. The course handout had specifically stated this. Primed by other courses in science, students assumed they would be graded on a curve. The fact that the professor posted a histogram after each exam with the break points for the letter grades may have confused them. The professor said later, "maybe the students think a histogram implies a curve." His classmates' behavior, however, suggested to Eric that they fully believed grading was on a curve.

> It wasn't until this afternoon that a classmate explained to me that students in a science class try to identify people who score well and then constantly compare their scores (or time studying or answers on homework) to their own. I have never been in a class before where my grade had any effect, real or perceived, on anyone else.

[8] Eric did very well in the class. He never got the grade on his final exam but he averaged 92 during most of the course. See below for more of his comments about the examinations and the grading system used in his course.

Even more basic, for Eric, was the class' fixation on grades.

> Why is it so difficult to get a good grade? For one thing, there are less of them. Due to [perceived] curving in physics, the grades are based on the class average which kills any spirit of enjoyment. The message (though surely not intended) seems to be that no matter how hard you work—so long as everyone else works as hard or has more talent or experience—you *cannot* improve your grade.

Eric found the "sense of competition" in no way beneficial. "It automatically precludes any desire to work with or to help other people," he wrote. "Suddenly your classmates are your enemies." No wonder the class was not "fun," and there was so much hostility between students.

> My class is full of intellectual warriors who will some day hold jobs in technologically-based companies where they will be assigned to teams or groups in order to collectively work on projects. [But] these people will have had no training in working collectively. In fact, their experience will have taught them to fear cooperation, and that another person's intellectual achievement will be detrimental to their own.[9]

Still, he was impressed with his fellow students. Although the class continued to look "tired and bored" to him, he noticed that they "stick with it." He found there to be a "much more practical attitude about this class" than he had experienced in humanities. People think "yes, this is dull, but I have to complete this course to get my degree or to get a good job."

> In my literature classes it was much harder to rationalize this way. People took courses mainly because of interest in the topic or because they thought the professor would be good. It is not that a science course cannot be or isn't interesting, only that it's not required or expected by the students that it be so.

While some of the concepts were difficult for him and he continued to be bothered by the "constant qualifiers" such as "assume a frictionless surface," it was the pace of the course that he found "excessive, almost insane."[10]

> I usually give myself three hours for homework and never finish...I feel, though, that I have sufficient control of the subject matter [studying this way] to do well on the exams.

[9] The issue of teamwork is a centerpiece of modern science. See Daryl Chubin et al, *Interdisciplinary Analysis and Research*, Lomond, 1986.

[10] The professor himself admitted that the pace was "preposterous." Mindful that a summer school course is not typical, we continued the experiment with semester-long courses in the following fall. See *infra*.

> Most of the other students I have talked to take six or seven hours a day to do the work...Aside from the pure misery of devoting that much of your life to physics, I wonder how much they, or rather we, will retain. I think that a slower pace and more in-depth discussions of the contents would, in the end, prove [more] beneficial.

He found the time demanded to be considerably more than he ever spent in literature—three hours per course hour in physics versus two hours per course hour in literature. Moreover, as he wrote during the third week, "physics homework demands a more intense, highly active type of thought."

> Reading, however critically done, is a more reflective activity. There isn't the demand for almost instantaneous application of the information. The result of this difference is that two hours of physics is much more demanding and tiring than two hours even of [academic] reading.

The drawbacks of this amount of time spent may not be immediately apparent, he wrote. However,

> with my extra time [as an undergraduate majoring in literature], I was able to pursue many different and independent types of educational experiences. Some of this included designing and running my own course, and [when an upperclassman] writing a grant-supported research paper. The science student is more often than not limited to the struggle of just completing required work.

When Eric asked himself, midway in the course, "what makes science hard?" he came to a preliminary conclusion that students will perceive a course to be "hard" when it is: 1) difficult to get a good grade; 2) time consuming; or 3) boring, dull, or simply not fun. Physics he found to be all of the above. But why introductory physics should be thought of as "dull" intrigued him. He kept coming back to the lack of community and the lecture format.

> The lack of community, together with the lack of interchange between the professor and the students combines to produce a totally passive classroom experience...The best classes I had were classes in which I was constantly engaged, constantly questioning and pushing the limits of the subject and myself. The way this course is organized accounts for the lack of student involvement...The students are given premasticated information simply to mimic and apply to problems. Let them, rather, be exposed to conceptual problems, try to find solutions to them on their own, and then help them to understand the mistakes they make along the way.

But the concepts weren't easy and sometimes they didn't get cleared up at all.

> For some reason I am unable or secretly unwilling to complete these statics problems. Nothing seems to make sense and for the first time since my initial anxiety attack, I feel a cloud of bewilderment around my head...Tomorrow will give me a good opportunity, however, to see what venues are open to a student who is "lost." I will try buying a solution sheet and see if the problems make sense. If they still don't, I will go to office hours, an activity I've always hated. Someone who is clever will always get by; but what of someone who isn't? Is the measure of a course how much a bright student learns or how much someone who is "lost" can be made to comprehend?

Getting help was not easy for Eric or, he thought, for the others, despite the small size of the summer school class.

> If you find you do not understand something from the last chapter, you must wait until after class to see either the professor or the teaching assistant. The professor's office hour is busy and there is not much time for in-depth help. The teaching assistant, while well-meaning, has problems communicating in English, and is only around on certain days of the week. Even if you start to feel that you understand, you are faced with the task of the next chapter's homework, so you really can't afford the luxury of spending yet another evening tackling the same problems.

As he lost some of his footing, Eric noted that it was much harder to "cram" for physics than for literature; hence it was not possible, as undergraduates are wont to do, to let the class "go" for a few days while he concentrated on something else.

The "best class" in Eric's view was one where the professor brought in five or six demonstrations, the results of which were counter-intuitive, and then asked the class to speculate as to why specific results occurred. In this class, there was substantial interchange. It led Eric to wonder whether a class could be designed that was "half lab, half lecture." But even more, he longed for study groups, arranged by the instructor for the class.

> The homework problems are hard and take an enormous amount of energy and patience. I think working together might engender an attitude that problems are enjoyable exercises...rather than aggravating stumbling blocks.

Worse yet, on any given day, the class worked on three separate chapters at once.

> Take June 13 for example. On this day, the professor answered questions on the homework problems from chapter 6, did some sample problems from chapter 7, gave us a quiz on the material from chapter 6, did some demonstrations pertaining to chapter 7, and began to lecture on chapter 8.

A consequence of the fact that students did their work "in private," Eric thought, was the absence of any opportunity for them to *talk* about the physics they were studying. They seemed inhibited, he observed, even about asking questions. Eric continued to do well on the exams and quizzes and was always surprised, even "shocked" at how low the class average tended to be.

> What this means is that there are a good many confused people sitting quietly and not asking questions. This is always the case to some extent in college, but physics seems harder on these people than the humanities. So much is based on what you should have learned the day before, that the course is a bit like a race where if you falter and don't immediately recover, you are sure to go down and be trampled.

The lack of "discussion" continued to fascinate and to bother Eric. He found that when he asked his classmates about what they were studying, they weren't able to "articulate an answer."

> I wonder if this is because they lack communication skills or because they haven't yet had the time to reflect on what they have learned, or perhaps because they don't really *know* much about their subject—if knowledge is defined to mean a deep, thoughtful understanding, rather than a superficial ability to regurgitate formulas.

One possible explanation might have been that in a course where answers are so critical, there is an inordinate fear of "making mistakes."

> One of the most frustrating things about the class is that the material comes so quickly. Once you stop "making mistakes" and master one chapter, you must move on right away to the next. Almost by definition, you wind up with more wrong answers than right ones. Learning physics becomes a process of making fewer and fewer mistakes, and moving on. There is no time to enjoy the success, no time to use those skills in order to discover more or dig deeper.

Still Eric was able to go deeper. He began to ponder the differences between mathematics and physics.

> Today I asked the professor why you figure *work* with a dot product. I got a different answer than I expected. Instead of talking about vectors and scalars, he talked about "what works." I realized that in physics, unlike math, you are much more concerned with getting real and usable figures than in the mathematical integrity of the operation. This is interesting because until this point, I did not really understand the difference between pure math and math as applied to science.

By the last week of class even the professor was "tired," or so he appeared to Eric. The class was but a shadow of what it had been. One-third of the students enrolled had either dropped out or were just not attending anymore. Eric noticed that the ratio of men to women, however, had remained about the same. The professor made numerous mistakes in explanation, and like everyone else, Eric thought, "just wants this class to be over." The "sudden shifts from particles to waves and then from waves to heat and temperature, without a pause, had everyone scrambling."

> There are no sad faces on this, the last day of class. No one will miss this chore. No one will say to himself or herself, "I really enjoyed that," or "that was an interesting learning experience." Instead, people will congratulate themselves on having made it, will be happy with their "B" or their "C," and will very soon forget anything pertaining to physics.[11]

For Eric, the final exam was a compressed version of everything that the course had and had not been, absent the "big picture." Eric had found all four exams in the class "biased toward computation and away from conceptual understanding." He understood that to be able to complete the computations required "some level of conceptual understanding." But that level was "not particularly high," he wrote.

> The problems [on exams] seldom required the use of more than one concept or physical principle. Only once were we asked to explain or comment on something rather than complete a calculation.

Eric thought the final, which was cumulative, would be the "... ideal place to tie things up and ask comparative and conceptual questions." Instead, he found that the questions entailed some fill-in-the-blanks definitions with terms found in a list. This caused him to reflect on the course more generally.

> We had marched through the chapters, doing the required work, but never digging deeper...I was able to keep myself on track by concentrating on one chapter at a time. But I never really got the idea that the professor had any understanding of how the concepts were related, as he rarely tied together information from more than one chapter. His lectures did not seem to build upon each other, and he gave no indication of a linear movement through a group of concepts...The final then asked the most primary basic questions about only the most important laws of physics. We were not required, at any time, to interrelate concepts or to try and understand the "bigger picture."

[11] Research by Hestenes et al confirms the failure of conventional physics instruction to overcome students' naive misconceptions about motion. Ibrahim Abou Halloun and David Hestenes, "The initial knowledge state of college physics students," and "Common sense concepts about motion," *Am. J. Phys.* 53 (II) Nov. 1985, p. 1043, ff.

It was not that the connective tissue was unavailable to the instructor; it was simply not featured. From the beginning of the course, Eric had liked the textbook and felt he had learned best from it. His ability to read through it on his own contributed to his early success in mastering the course. He noticed right away that the daily homework included an approximately equal number of two very different kinds of questions. One kind, for Eric, were only "exercises" and were assigned as homework problems. At one point in his journal he described these as "mathematical in nature and varying in difficulty from easy to nearly impossible." The second kind of questions were of a more "complex, conceptual nature." This latter kind interested Eric very much, but

> ...[since] these questions were never even mentioned by the instructor after the first day, nobody ever bothered to look at them. I feel that the professor misjudged the value of these questions and missed an opportunity to use them as launching points for discussions of the concepts.

After the final exam, Eric wrote that for him "the greatest stumbling block to understanding" was the lack of identifiable goals and the absence of linkage between concepts. He noted these deficiencies in answering a question we had posed: what makes science hard in general and for students like Eric coming to these disciplines as outsiders? He wrote:

> To some extent science is hard because it simply *is* hard. That is to say, the material to be learned involves a great many concepts, some of which are very counterintuitive. The process of mastering these concepts and being able to demonstrate a computational understanding of actual or theoretical situations requires a great deal of time and devotion. In my experience, this fact is well understood by the students, the professor and the general public. What is not as well understood are the various ways in which this already hard subject matter is made even harder and more frustrating by the pedagogy itself.

He feels that some "skeletal plan" would have helped him enormously to see how each individual property and theory is related to the "big picture." Comparing his introductory physics experience with that of the humanities, he wrote, "A professor who lectures on American literature of the 19th century might oversimplify the various social factors involved in each novel by referring to long-term historical events and trends, but at least his or her students would have some foundation on which to build impressions and judgments of the works."

The other "most difficult aspect" of the course for Eric was the "lack of student involvement" in lectures, and in discussion outside of class.

Simply being "talked *at*" suited this particular literature student not at all. He attributed his classmates' inability to articulate their subject matter directly to the fact that they got no practice "talking physics" in class.

Finally, he concluded, the "pressure involved in grade wars" goes much too far. He leaves us with the following advice:

> If one is truly interested in reforming physics education in particular and science education more generally, de-emphasizing numeric scales of achievement and rethinking the grading curve is certainly one place to start.

Discussion

The course we chose for Eric was a summer session version of the two-semester, calculus-based, introductory physics course which generally serves the "weeding out" role for chemistry, physics, engineering, and at some institutions, premedicine and biology.

The course is standard in its scope and sequence, so standard in fact, that four textbooks together dominate the postsecondary market. (One of them, the one Eric was to use, has more than a 60 percent market share.) Instructors justify their choice of one or another text based on the "quality" of problems and minor variations in the sequence of subject matter. Because it "serves" so many other fields, a course like Eric's will be taken by upwards of 100,000 American college and university students each year, of whom about 1,100 will go on to get the Ph.D. degree in physics. (Another 150,000 study the less rigorous, noncalculus-based introductory physics course.) One structural problem exists at the outset: the professor is training physicists; the students, for a variety of reasons, are taking physics.

When we had Eric's professor read what Eric had written about the course, this disparity was made very explicit. Eric's professor wrote:

> I assume that students in 103 are preprofessionals who have already decided on a career in science and are in class to learn problem-solving techniques that will be required of them in their careers...I [also] assume, however less and less, that the students have had some hands-on experience with how things work: clocks, cars, radios...and some experience with, and curiosity about, the physical or natural world. In other words, I assume I can make analogies to get across physical concepts. Students not interested in the physical world have a harder time, since they don't know, and usually don't care, how *things*, cars, bodies, weather, the heavens, work.[12]

[12] Personal communication from the professor to the author.

Eric complained that the "goals" of the course were never clearly articulated, and that the chapters were insufficiently "linked" or made to cohere. This was in part because of the fast pace of the summer session course, but also because the "unity of physics," assumed by the instructor was not explained often enough. Eric yearned for more "conceptual" information (we think he meant "interpretative"), and not just "facts" and the "mechanics" of problem solving. His professor was aiming his course at a different student. The teacher believed that, had he asked for any greater in-depth reasoning in class or on exams, there would have been "sheer panic."[13] In fact, he was adjusting his course to the needs and the limitations of the students he assumed he was teaching. Eric was asking for a different kind of adjustment, one directed to his intellectual curiosity.

According to Sharon Traweek, an anthropologist who studies the values, training and work styles of high energy physicists, Eric's complaints would not be perceived to be significant by professors whose goal is to train future physicists. From her interviews, she concludes:[14]

> [Successful] undergraduate physics students must display a high degree of intellectual skill, particularly in analogical [pattern finding] thinking. The students learn from textbooks whose interpretation of physics is not to be challenged; in fact it is not to be seen as interpretation. They learn to devalue past science because it is thought to provide no significant information about the current canon of physics, but they also learn from stories in their textbooks that there is a great gap between the heroes of science and their own limited capacities...
>
> [The emphasis on problem-solving is meant to] show students how to recognize that a new problem is like...familiar problems; in this introduction to the repertoire of soluble problems...the student is taught not induction or deduction but analogic thinking.

There are several ideas to be taken from the Eric experiment. Something besides the traditional problem-solving approach may be needed to excite *new* students to physics. But at least as important as content, if Eric's reactions are typical, will be changes in the "classroom culture" of physical science: more attention to an intellectual overview, more context (even history) in the presentation of physical models, less condescending pedagogy, differently challenging examinations, and, above all, more discussion, more "dissent" (even if artificially constructed), and more "community" in the classroom.

And what of the ten students who "disappeared" from Physics 103a

[13] *Ibid.*

[14] Sharon Traweek, *Beamtimes and Lifetimes, The World of High Energy Physics*. Cambridge: Harvard University Press, 1988, pp. 74 and 75.

last summer? Eric had no idea whether they had dropped the course or had simply stopped coming to class. In the "old days," a former chairman of the department told me, the course instructor would sign every course drop card, so there was opportunity for an "exit interview" and for some conversation about the course, the student's career goals and his or her alternate plans. Although Eric's professor did see a number of "drops" because of his advertised approachability, today drop-cards are handled bureaucratically by staff. Hence, there is less opportunity for retrieving the failing student or for soliciting students' views about particular courses.

If the science shortfall is to be stemmed at college, many more students should be made to feel welcome and valued, whatever their capacities and degree of commitment to science. The truth is science can be done by people who are not necessarily younger versions of their professors. Despite the emphasis in science on the "heroes" who contributed to what Thomas Kuhn calls "paradigm shifts" in the disciplines,[15] the scientific method was originally promoted by Francis Bacon precisely because it enabled "conventional minds" to do science.[16] Surely there is room in Kuhn's "normal science" for a larger portion of the college population than is currently made to feel deserving and comfortable in science. There is reason to believe many more undergraduates would respond to a differently constructed introductory course.

To an uncertain adolescent, flailing about for something he or she might actually be able to *do* and do well, science offers not just a whole array of interesting and important careers, but a training that, to paraphrase Bacon, enables ordinary people to do extraordinary things. If physicists learned to regard *every one* of those 250,000 introductory physics students—most of them somewhat better than "ordinary"—as having something valuable to contribute and much to gain from science, there might be no science "crisis" at all.

[15] Thomas Kuhn, *The Structure of Scientific Revolutions*, Chicago: University of Chicago Press, 1962.

[16] Francis Bacon, *The New Organon and Related Writings*, ed. Warhat, pp. 353-358, as quoted in Sharon Traweek, *op. cit.*, p. 80.

Jacki and Michele

The themes that emerged out of Eric's encounter with summer school physics were to surface again and again as the project continued. Mindful that summer school is extraordinarily fast-paced and that not all students would be as intellectual or as self-reflective as Eric, we developed a longer project in the fall of 1989 that would place six nonscience students as participant observers in semester-long introductory chemistry and physics courses. While the experiment did not consciously seek out the full range of potential second tier stand-ins, a somewhat diverse group of students responded to our invitation, among them Jacki Raphael and Michele Schoenfelt, graduate students in creative writing and philosophy, respectively.

Like Eric, Jacki and Michele had enrolled in and enjoyed science in high school but, for different reasons, had not pursued science at college. Yet, they rapidly forged ahead in their introductory physics course at the University of Arizona, demonstrating that above average intelligence and motivation, when combined with the power to reflect on what one is learning, contribute substantially to success in this field. While physics itself delighted and fascinated them, they found that the "logic of presentation" and the classroom culture still left much to be desired. The course in which we placed Jacki and Michele, Physics 111a, is an introductory calculus-based physics course, the first of a new four-semester sequence designed to capture potential physics majors immediately upon their arrival as freshmen. Normally, students interested in physics begin their freshman year with college calculus and only start physics in the spring. Fearful of losing them and of breaking the continuity of their high school-college sequence, the department of physics has created Physics 111-112 as an alternate physics sequence. In the first semester, the missing calculus concepts are taught along with mechanics; then three semesters (instead of two semesters) more are spent completing the introductory text.[1] Jacki's calculus skills were rusty but quickly came back. Michele was weaker in calculus and hence had more difficulty with the course.

Jacki

Her professor said of Jacki after she completed the first semester of Newtonian physics, "She could easily have been a physics major, and a

[1] Halliday and Resnick, *Fundamentals of Physics*, Third Edition, *op. cit.*

good one." Indeed, Jacki has the temperament of a scientist. She likes intellectual challenges and chose English over science as an undergraduate at Yale because science, as she thought about it then, was not sufficiently challenging. She brought to college a strong science background from a fine suburban high school in New Jersey. She had even, as she put it, been "programmed" to some extent to do science at Yale. But until we invited her to seriously audit Physics 111a at the university last fall, she had been a science avoider. She was enthusiastic about what lay ahead:

> I had good memories of high school chemistry and physics and imagined that, six years later, I would find college physics challenging and interesting. As a 24-year-old graduate student in creative writing, I was free from the career and grade concerns experienced by the average college freshman. I had the luxury to concentrate on satisfying my intellectual curiosity and, as I traveled, to reflect on my journey.

She used the term "journey" with its hint of magic because everything about the first physics lectures foreshadowed an intellectual adventure. She liked the fact that her professor was excited about teaching and about his subject. But, perhaps because she is trying to become a writer, she noted right away that her professor did not "narrate" his subject. He rarely told the students what they were doing or where they were headed. As a consequence, Jacki found herself faced with two disparate tasks: first, to understand the material being covered; second, to decide for herself how each part of the lesson fit in with the others. To accomplish this, she began to "construct my own narrative." She enjoyed the process but worried whether her narrative would correspond to the professor's. Like Eric, she was frustrated by a "missing overview," what physicist John Rigden, in amazing resonance with Jacki's own metaphor, calls the "story line."

> Why, I wanted to know, did we begin by studying only the idealized motion of particles in straight lines? What about the other kinds of motion? If he could tell us what's coming next, why we moved from projectile to circular motion, for example, I would find it easier to concentrate; I'd know what to focus on. In college, I always wanted to know how to connect the small parts of a large subject. In humanities classes, I searched for themes in novels, connections in history, and organizing principles in poetry.

How was she going to find connections in physics?

In time, she defined more precisely what she meant by "narrative:"

> In science in particular, teachers need to narrate with comments such as "what we didn't resolve last time" to let the class know when it is plunging deeper into the material. [He needs to] show us how the subject is put together, its *grammar*...Not that you could not speak a foreign tongue without knowing the definition of a predicate. But in order to follow in lecture, I like to be told what I'm learning in terms of the language of the whole.

Apart from the missing story line, Jacki found the lectures extremely interesting and, at the beginning, the homework relatively easy to do if she put in the time. The course demands in general, she wrote in her journal, were "realistic and attainable with honest effort."

> If you work the problems, you will most likely be able to solve them...That's what makes physics easy.

But, like Eric, Jacki was bothered by what she felt was an "exclusive" problem-solving focus. She noted that students put down their pencils when the professor discoursed on Aristotle, Galileo, and the history of science. They appeared to enjoy these excursions, but treated them as a kind of relief from having to concentrate so hard. Indeed, when she worked with the students in her study group, she realized that, as a rule, they did not want to talk about the problems conceptually.

> Their concerns focused on the kinds of problems they would encounter on the exams, and not at all on a general understanding of the concepts...They ignored all the fun parts, seeing the whole picture, laying out the equations and solving these. Instead, they wanted to know what equalled what and solve for an answer. The elegance of problem solving was lost...

Jacki clearly had another agenda. After the second quiz, she wrote:

> I wonder if I am different from the others...I don't care if I can solve standard physics problems easily. I want to get better at the tricky ones, the ones that ask me to use the concepts of physics.

Like the other second tier stand-ins Jacki was distracted by questions that were left unanswered, gleeful when she grasped, just before Thanksgiving, that "all along we were leaving things out in order to establish the basics and then move toward a fuller understanding of phenomena." And she was ecstatic when, toward the end of the semester, her professor paused and let her discover for herself why they had spent so much time "looking for laws of conservation." "Physicists," she finally figured out for herself, "want to locate permanence in change, the better to describe change." She guessed that most students in the class weren't "thinking much about such issues, but rather just writing notes, hoping they would absorb the material later." By midsemester, she thought the students around her had become resigned to merely "taking dictation."

> They have given up and don't even attempt any longer to follow the lecture. Not because the material is too complicated...I think theirs is a crisis of confidence and effort.

One day waiting in the professor's office while he "walked" a student through a particularly difficult homework problem, Jacki saw such a "crisis of confidence" on display. After struggling with a problem for a while, the student panicked and blurted out: "You can't put that on the exam. I'd never think of that!"

Jacki was not altogether free of anxiety herself. She was getting "A"s on her quizzes but described herself as quick to panic when insight didn't immediately come as she tackled new material. "Learning to solve physics problems," she would tell herself, "is a process, not a matter of insight." In her journal she attempted a definition of "understanding" as applied to physics. "Understanding the free-body diagrams means *knowing how to do them!*" But watching the professor do them was not enough. On a particular day, she noted:

> When he goes through these problems the work seems so obvious, the equations so inevitable, that I tend not to question what he's doing...Lectures in physics can be incredibly passive experiences for students, particularly dangerous for those who believe [as Jacki sometimes did herself] that if they can follow the professor, they've mastered the material.

When she worked on her own, Jacki felt the "thrill" of understanding concepts and solving complicated problems. Yet, she found herself still resisting the *practice* required of her in physics. She speculated that it was not laziness, but rather

> ...the remnant of a prejudice of mine. Especially in the humanities, I value intelligence over technical mastery...I have come to see here that *intelligence is part craft*.

By the time the midsemester exam came around, Jacki was ready for much more than was forthcoming. Like Eric, she found the exam to be "nothing like the homework problems."

> It was simple. It didn't really test understanding. There weren't elegant problems to solve. There were so many things I thought I was going to have to know that weren't on the exam: that normal forces are what a scale reads, the direction and nature of frictional force, that friction occurs toward the center of a circle against the bottom surface of the tires of a car rounding an unbanked curb, the difference between kinetic and static friction, what an inclined plane does to a free-fall, which angle is the bank angle, etc. I don't completely get all of this. But these are the questions I was thinking about when I prepared for the test.

These questions grew out of Jacki's "metathinking" about the problems she was trying to solve. It fascinated her that the two masses (inertial and gravitational) were independent of one another (within the scope of Newtonian mechanics); and that forces have regular, predictable components. "How organized the universe is!" she sighed one night into her journal. But she sensed that her fellow students were not able (or willing) to pursue such ideas.

> I think the students around me are having the same sort of thought-provoking questions about the material that I put into my journal, but under time pressure they don't pursue them, [and] eventually they learn to disregard "extraneous" thoughts and to stick only to the details of what they'll need to know for the exam. Since the only feedback we get is on the homework assignments, the students cannot help but conclude that their ability to solve problems is the only important goal of this class.

What would have served Jacki better was a more question-driven sequence.

> If a phenomenon acts on or affects two things, will the two be affected in the same way? This is the sort of question I like. I wish physics lessons could be presented as answers to such kinds of questions.

Also she wanted more time and space to speculate about the fundamental paradigms themselves. Once in a period of frustration trying to come to grips with the law of conservation of energy, she decided that it was so "artificial" as to be "bogus." "When energy is lost to friction, you have to include heat as energy to make the balance come out right," she wrote, and this bothered her. Later, she got her professor to explain to her privately that

> ...mechanical energy is really just part of the physicist's way of explaining conservation, a way of freezing a system at a moment of time, a descriptive tool, but not a tangible amount of energy per se...I really liked this. I felt I was learning something very important about physics. I don't mind if formulas are used to describe strange, unknowable quantities, or relations that are necessary merely for consistency. Language is such a system, philosophy for sure. I like that aspect of physics. I just want to be certain I can see why and how physicists describe the world.

Because Jacki's math confidence was high and her calculus skills rusty but still in place, she was able to stand back from the computations and contemplate the *relation* between physics and mathematics. When one day, working two simultaneous equations, her professor advised the class to try squaring both equations to eliminate one variable, Jacki was fascinated that an algebraic manipulation would "work" in physics. She knew that "you can't understand the physical world not knowing math," but wondered more profoundly, "how math is intrinsically related to the physical world."

Her appetite for the overview was finally being satisfied, if only by the questions that "distracted" her and by the narrative she was constructing. Toward the end of the course, she could chronicle her own progress.

> When we first did physics problems we ignored certain variables: friction, heat, and the pulleys over which cords ran with masses on the ends. Problems with parts such as inclined planes were idealized to be smooth, frictionless, simple. As the semester progressed, we gained the technical means to quantify friction, how to take the rotation of a pulley into account. Now we can study the effects of forces in more detail. We can describe the decelerations of a billiard ball, for example, after it has been set in motion and until it comes to rest. Things that used to be simple in our problems are complex.

But why didn't her professor "tell us this was how we would progress? Why did he wait to the end?" One answer might be that, in science, students cannot understand where they are headed until they get there. But the frustration for Jacki was real and made her, like Eric, feel much like a child.

> I never really knew where we were heading or how much, in the real scheme of things, we had already covered. Each topic the professor discusses feels like it's being pulled out of a hat. So the general feeling I was left with was that physics was endless, that there would always be one more complex way of describing motion...I was made to feel too much like a naive child, whose parent tells me one small thing at a time, making everything seem equally mysterious.

Part of this was the "ownership" issue that Eric had felt, too. Jacki liked and admired her professor but felt she could not share in the "intimacy" of his relationship with physics.

> *He* knows the whole picture, how to solve complicated problems, even to talk philosophically about the problems and the issues of physics. *We* have but a fraction of that intimacy. There are whole areas we know nothing about. We don't even know these subtopics exist. That's how ignorant we are. His goal may be to get us to understand physics the way he does [but] his method, inevitably, is that of a grade-school teacher because we are like grade-school kids.

In contrast to her humanities classes, where

> ...you're encouraged to think on your own. Sure, the professor gives you background material and provides the details you will need to know to analyze the subject. But the *approach* is what is being studied. You can disagree with your professor's approach. And the moment you begin thinking *about* what the professor is saying, you're on your way to developing your own unique relationship to the material. The way we think about physics is not an issue in class. We don't know enough. The best we can hope for is learning something about how the professor thinks about physics.

In the end, Jacki was not enthusiastic enough about physics to let it change her life. She did agree to take the second half of physics 111, hoping it might rekindle that initial "spirit of adventure" she had looked forward to in early fall. She felt, on balance, that physics was presented as a "race to get control of a specialized knowledge," and that "this striving for mastery" made physics not the *intellectual experience* she had hoped it would be.

Michele

Michele Schoenfelt was a first-year graduate student in philosophy when she agreed to audit Physics 111a. She had begun college with a strong interest in science, but except for introductory astronomy, she had taken none—this, despite the fact that in high school she had been primarily a science student in the advanced math and science track at a good, large public school. "Back then I took virtually no humanities classes and all the science I could get my hands on," she wrote in her journal. This included one year of physics, two years of chemistry, and two-and-a-half years of biology. She had mathematics through trigonometry and was, beginning in her sophomore year, a lab assistant for biology and chemistry. As she remembers, she did very well in her science classes, enjoyed them immensely and even participated in the Physics Olympics. Leaving high school, she fully expected to earn an advanced degree in "something like organic chemistry."

What dissuaded Michele was a combination of events: a freshman's reluctance to take classes that, as she remembers, "all started at 8 a.m.," and a number of "discouraging experiences."

> One of my counselors had started out in biochemistry and warned me that a lab was a very lonely place to work. The introductory astronomy class which I had expected to love turned out to be quite bad. It was a lab only in name. The professor used the weekly hour of lab time to make us do nothing but computations on paper. He had promised we would be allowed to use the observatory; he never lived up to that promise.

Instead, during her freshman year, she began a lifetime "love affair" with philosophy.

Like Jacki and the others, Michele was enthusiastic about the opportunity to take physical science for the first time. She brought to the subject a true curiosity about the physical world and an expertise in those branches of philosophy that would be particularly relevant to her work as an observer: logic and epistemology. Like the others, she attended classes, did homework assignments and took two of the four hour exams that preceded the final. Then, instead of preparing for the final, she polished up her journal and wrote for us a reflective essay on her experience.

Unlike Jacki, Michele found the mathematics very difficult (she was not as well prepared), and that it "intruded" on her search for mastery of "concepts." But the content was not as difficult for Michele as it was "demanding:"

> I spent more time doing physics than I did working on any one of my graduate-level classes in philosophy. There was always homework, even on the day an exam was scheduled. Homework problems were supposed to take about 15 minutes, but they usually required much more time. Review sessions and exams were piled on top of class hours, i.e. scheduled out of class time. You really have to be committed to a subject to be willing to devote that much time to it, semester after semester.

She also experienced "discouragement" caused by failure to master the next level of problems quickly and easily. But, as a philosopher, she was able to reflect on the experience. Science, she noted, demands that one not be discouraged by failure:

> In solving problems you are expected to make many mistakes. By the time you eliminate your mistakes you're off to a different type of problem...This causes enthusiasm to wane.

Like Eric, she was bothered by the lack of "creativity" demanded of her and by what she thought was a requirement for excessive conformity.

> Science demands that you do your work the way the instructor does. It allows [at this stage] for precious little interpretation. This is as it must be, but if you don't like this, it can be difficult to force yourself to conform.

But most of all, Michele fretted over the dominance of the quantitative.

> My curiosity simply did not extend to the quantitative solution. I just didn't care to figure out how much. I was more interested in the "why" and the "how." I wanted verbal explanations with formulae and computations only as a secondary aid. Becoming capable at problem solving was not a major goal of mine. But it was the major goal of the course.

As a student and sometime teacher of philosophy, Michele was very able to grasp what bothered Eric about the lack of "explanations." She found herself "obsessed," as she put it, with gaining a "discursive understanding" of a concept before using it. But she was more willing than Eric to acknowledge that "sometimes you have to accept procedures just because they *work*." She began to appreciate that "understanding comes with practice," but still found herself spending a lot of time "banging her head against the wall." Her physics course demanded more patience than she was very often able to deliver. Moreover, as Vicki was to conclude (see *infra*), the way the course was taught did not play to her strengths.

> Science demands that you work in an orderly fashion. If you're accustomed (as I am) to solving problems by using shortcuts and doing as much as possible on the calculator without writing things down, you get into trouble...

Besides the demands made on students, Michele found a number of things which "in combination" were alienating. She listed these as:

> Too little time allotted to simply reading the text. This reinforces the message that doing problems is all that is called for.
>
> A course design that assumes that everyone in the class has already decided to be a physicist and wants to be *trained*, not *educated*, in the subject.
>
> The absence of a "road map," and the feeling that "curiosity questions" have no place in class discussions.
>
> Too easy exams in contrast to too hard homework. On philosophy exams, Michelle noted, instructors expect their students to do more than what they've done before, not less.

Contributing to her sense of frustration was the homework schedule. Homework assigned at the beginning of one class was due at the beginning of the next. As a result, she noted, there was no chance to ask questions in class about the homework before turning it in. And after it was turned in, little motive to ask questions about difficult problems or to strive to understand them even if they were explained. Michele thought a larger set of problems, given at the beginning of one class and due two classes later, could have promoted greater class interaction, and more effort expended on difficult problems.

Michele was acutely aware that physics required her to reverse her usual method of learning. "Performance," she wrote, "comes before competence." She understood that many concepts in science are best grasped via manipulation and experimentation. But she found this "performance first, competence later" sequence capable of paralyzing, or at least considerably frustrating, certain students who would say, if they could articulate their problem, "I can't use it unless I understand it, and you tell me I have to use it in order to understand it."

Beyond her desire to learn concepts more "discursively," Michele did not find physics concepts particularly difficult to master compared to abstract ideas in other fields. But she did offer some insights into why some intelligent students may decide to leave science:

> If creative, innovative students are to be retained in greater numbers, instructors are going to have to...give them more of a sense that they are not just walking down the same trodden path of problem after problem to solve. Students need to know the goals, the structure, and the way science and mathematics relate [so that they can exercise] their curiosity and critical thinking powers.

Discussion

As the preceding amply demonstrates, Jacki and Michele were quite capable of grasping the scope and purpose of their physics course. But this in no way reduced their impatience with the emphasis on problem solving. As Michele put it, there were too many "how much" questions, not enough discussion of "how" or "why." Individual problems intrigued and, on occasion, even delighted all of our second tier stand-ins, but only when they led to understanding and did not merely test skills. For several of our auditors, and as Tom Worthen would write in his journal (see *infra*), the problems were of limited interest because they had "all been solved before."[2] Only occasionally did these exercises provide intellectual satisfaction; rarely were they a source of new insight. Our auditors mastered physics problem solving as well as most of their peers (with the exception of Vicki; see *infra*). But they looked upon the effort, almost without exception, to be *training* at the expense of *education* in science; too many scales, not enough music.

For their professors on the other hand, *proficiency* at problem solving is more than a disembodied skill. It is the essence of their subject and of their pedagogy, the very core of the introductory course. Instructors in physical science who teach beginners believe that problem solving contributes to at least three of their teaching goals: 1) imparting the basics of the subject (Newton's laws, atomic and molecular theory, the periodic table); 2) explaining how physicists or chemists make sense of natural phenomena—how they think and what they do; and, 3) preparing students who continue in science for what lies ahead. To do all of this most efficiently, they focus on the quantitative nature of the concepts. So the concepts of force, field, valence and oxidation states,

[2] Physicist John Rigden of the American Institute of Physics, quoted before, says that many of the brightest physics majors are bothered by this as well.

molarity and chemical equilibria are presented not as "words" or "ideas" not even as "explanations," but rather as embedded in techniques.

This goes far to explain why our auditors perceived their courses to be low on "concepts," even on "theory," and why they felt mired in "facts." (Jacki at one point called these "dry formulas" and "dull reality.") Michele came closest to speaking for all when she characterized herself as "not impressed" by the fact that something works (a formula or a model) unless she was given, in addition, a "discursive understanding of the idea." Perhaps what we have here is not so much a disagreement about content as a problem of communication. The second tier stand-ins felt that the "formulas came too fast." They wanted more time to wrap their own intelligence and intuition (their "creativity") around exploratory questions; to be given the formula or the explanation only later when they had exhausted their own imagination; and to learn the appropriate technique as a *means* toward solving problems, not as an *end* in itself. As Tom noted, to take but one example from chemistry (see *infra*), more attention was given to Avogadro's number (merely a conversion factor from atomic mass units to grams) than to Avogadro's insight! A typical complaint.

A difference between our stand-ins and many of their fellow students was their skepticism about models. Eric had problems accepting the idea that constrained motion has to be understood in terms of forces. For a while Jacki regarded the law of conservation of energy as "bogus." Michele marveled that the physicist's model of reality could be so "unreal." That something works (a formula or a model) was not sufficiently persuasive. Had their professors time for some history of physics, they might have better understood why these models work. Eric eventually became comfortable with the notion that any environment, including any constraint on an object in motion, has to be described in terms of a set of forces. Jacki finally understood, profoundly, that the law of conservation of energy is defined so as *never to fail*.

Professors encourage these insights. Indeed, they reveal them to students all the time. But they teach as if these insights will emerge naturally from the experience of setting up quantitative problems and solving them, perhaps because this is the way they were taught or because this works for them. While for many students this is the way understanding comes, for Eric, Jacki, and Michele it was patronizing not to be told in advance where they were headed, or what they needed to know to understand. That's why the experience conjured up for Jacki the image of herself as a naive child whose parents tell her one small thing at a time and keep the whole mysterious.

The challenge for the teacher of beginning physical science is to teach techniques, along with the sophisticated concepts that underlie the techniques, without either patronizing students or cheating them of the creative and critical thinking that science also entails.