HOW TO SOLVE A PHYSICS PROBLEM: NEGOTIATING KNOWLEDGE AND IDENTITY IN INTRODUCTORY UNIVERSITY PHYSICS

by

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Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the Degree of

MASTER OF SCIENCE

IN

SCIENCE AND TECHNOLOGY STUDIES

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April 20, 1996

Blacksburg, Virginia

Keywords: Physics, Problem-solving, Identity, Education, Ethnography

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ABSTRACT:

In this project I study introductory undergraduate physics classrooms as critical sites in the development of students' relationships with physics. Drawing on interviews with students, observations of classrooms, and analyses of textbooks, I compare introductory undergraduate courses in physics required for engineering majors, physics majors, and students in the life sciences, respectively to understand the ways that students in each class come to understand themselves as physics learners. Some of the students whose stories I will attempt to capture are learning to think like physicists, some are learning to incorporate physics into their engineering work and method, some are learning what role physics might play in their lives if they will be neither physicists nor engineers. All of these relationships depend on particular assumptions about what it means to become a physicist, or an engineer, or a biologist, or a non-scientist. In short, they are all thoroughly intertwined with identity. What I want to understand about learning physics is what it has to do with identity--how it participates in the fashioning of different kinds of student selves, and how in turn those student identities participate in defining and maintaining the disciplinary identity of physics.

Acknowledgements

I have certainly endeavored to properly cite those people whose words and ideas I have drawn on throughout this document, but there are several people whose contributions to my work and growth I can't capture simply with footnotes. My deepest gratitude to Peter, for managing to be very present in this text and the process of its production even from halfway across the country; to Jan, for steering me through the complexities and ambiguities of ethnographic practice, and for putting up with lengthy emails demanding explications of social theory; to Barbara, for helping me to make connections across literatures, and for providing the seminar environment and thoughtful feedback in and through which I was first able to work out the 'theory' of this project; to Steve, for keeping me honest and responsible to physics and physicists as I write about them; and to Gary, for challenging me, for helping me to find my direction into this thesis and beyond it, and for teaching me about theorizing and practicing intervention. Also, for two years of support and stimulating conversation, my thanks to my fellow STS students, particularly Heather for reading drafts, and all those comrades who entered the program and moved through the core with me last year. And of course, thanks and love to Laurie, Bonnie, Silver, Mom, and Dad, whose endless contributions don't need recounting here.

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Chapter 1: Framing the Problem

Introduction: Joking about Identity

Three university students, one majoring in physics, one in engineering, and one biology, are sitting together in their favorite campus coffee shop, and the conversation turns to the three different introductory physics classes they are taking this semester. The engineering student begins: "you know, I'm pretty happy with my physics class, and the professor really knows his stuff, but it seems like we could accomplish a lot more in class if he'd stop with these useless derivations and spend more time working examples. Imagine how many more problems we could go over in a class if he'd just skip all that theory and get down to plugging in numbers." Pulling out a calculator, she continues, "in fact, in a 50 minute lecture, allowing 4 minutes for the professor to go over administrative details at the beginning of class, and 30 seconds for him to ask, 'are there any questions?' and politely wait for a reply while we sit in silence, and a minute and a half for him to set up each problem..."

As the engineering student intently accounts for variables and taps at her calculator, the biology student forms a troubled frown. After puzzling for a moment, he says, "I don't know, I'm not worried so much about how *many* problems we go over in class as *which* problems we go over. I pay attention in class, and I read the book and all, but what's the point in learning how to solve these problems in class when we have to do completely different problems on the test? Maybe if the professor would just choose a few problems for each chapter, and show us how to do those, and we could go over them in class a few times, and then do the same problems for homework, and then practice those same solutions some more on our own, and then if those same problems were on the tests...then maybe this stuff wouldn't be so hard. What do you think, Albert?" Both students turn to look at the physics major, who has been quietly but furiously writing things on the back of an envelope he'd pulled out of his pocket while his friends talked.

Albert, the physics major, looked up from his work. "I've been listening to your concerns, and I think I've formulated a way to help you both to understand your classes better. If you draw each problem as a vector arrow, and imagine the professor as an object of mass M centered at this point..."

This story is, of course, a joke. And though it may not be particularly funny, it certainly follows the pattern of a tradition of physicist-biologist-engineer jokes, physicist-mathematician-engineer jokes, physicist-psychologist-engineer jokes, and so on. I haven't thoroughly researched such jokes to find out what other combinations of professions they might include, how widely they are told, or how much the format varies, but I can attest to their popularity and frequency among physics students, and I've also heard them told by engineers and mathematicians[1]. What's compelling about jokes of this genre is that they all depend on stereotypes, on idealized conceptions of physicists, mathematicians, psychologists, biologists, and engineers which we can all recognize, and which they can recognize in themselves. The order in which the characters play their roles varies--the physicist isn't always the butt of the joke. In fact, the butt of the joke is often in the eye of the beholder; the engineer might think the physicist is the fool for abstracting real-world situations into mathematical formalism, but the physicist will surely be equally amused by the engineer's obsession with details.

Furthermore, my joke has a twist on the standard format--rather than depicting fully-trained professionals in each field, it captures three students early in their undergraduate education. Catching the students in mid-stride like this raises a troubling question for the premise of the joke--should these students already, as freshmen and sophomores, betray in their words and actions the same degrees of conformity with the

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[1]The physicist Lawrence Krauss (1993) begins Fear of Physics with such a joke (his features a physicist, and engineer, and a psychologist) in order to "illustrate how--at least metaphorically--physicists picture the world." (p4) Krauss does not comment on the joke's equally powerful illustrations of how engineers and psychologists might view the world.

stereotypes as the adult practitioner, suggesting that each was somehow born with such tendencies, or began displaying them long before they arrived in their respective undergraduate curricula? Or should they be less likely to reflect the labels because they haven't had enough time to be molded by their respective disciplines? To put it simply, are physicists, engineers, and the like made, or born? To grapple with this difficulty, I made my joke characters by drawing on images from my fieldwork among introductory physics classes. The characters' lines are stitched together from interviews with students and professors, and from my field notes about classroom observations.

Like the joke, this thesis is about identities. Different labels, here "physics major," "biology major," and "engineering major," connote layers of meaning and information about the persons to whom they refer. In this project I study the introductory undergraduate physics classroom as a critical site for determining students' future relationships with physics. I compare three introductory undergraduate courses in physics: "Principles of Physics" for engineering majors, "Foundations of Physics" for physics majors, and "General Physics" for students majoring in sciences other than physics or chemistry. I intend to show the ways that students in each class come to understand themselves as physics learners. Some of the students whose stories I will attempt to capture are being taught to be physicists, some are being taught to use physics to make them better engineers, some are being taught what remains for them of physics if they will be neither physicists nor engineers. All of these relationships depend on particular assumptions about what it means to become a physicist, or an engineer, or a biologist, or a non-scientist. In short, they are all thoroughly intertwined with identity. What I want to understand about physics pedagogy is what it has to do with identity--how it participates in the fashioning of different kinds of student selves, and how in turn those student identities participate in defining and maintaining the disciplinary identity of physics.

I conceptualize "education" as emergent from the interplay between pedagogy, in the form of instructors, texts, assignments, lectures, and so forth; and identity, as it takes shape in learners, student "selves" who become increasingly adept at performing a particular role in a physics drama--one of a limited set of available roles delineated by the disciplinary scripts with which they must align themselves. Highlighting the problem-solving activities in which these students routinely engage both in and out of class, I claim that the three distinct sets of professor, curriculum, and students I studied enact three different "physics." In Foundations of Physics, physics is a powerful conceptual framework for making mathematical sense of the physical world. In Principles of Physics, physics is a useful tool on which to draw to build machines that work and bridges that don't fall down. In General Physics, physics is a collection of concepts and equations with which students must become sufficiently familiar to pass the course and fulfill the requirement toward their own majors.

By tracing these three distinct realms of physics activity, I aim to problematize a set of categories ("physicist," "engineer," and "'soft' scientist" or "non-scientist") which impose tight boundaries on the learning experiences of students. In other words, students' access to and understanding of physics are limited to and defined by the category into which they fit. These categorizations have consequences for students' lives; those lives are, after all, far more complex than three categories allow for, and students who wind up in the wrong physics box, or don't fit into any of the boxes, often slip through the cracks.

Overview

In the rest of this chapter, I will review literature on undergraduate physics education and on problem-solving, and then show how I intend to draw on those literatures and others to make sense of the physics classes I studied. Over the next two chapters, I will endeavor to tell a story with two sides. Chapter 2 will be about the curriculum, broadly construed. Here I will combine the professors, both as they appear in class, and in private interviews with me; the textbooks; the syllabi, the homework, and so on. Chapter 3 will focus on students. I will use both my words and theirs to capture some of the flavor of the "types" of students that emerge in each of the three classes. As I document pedagogy, curriculum, knowledge, and student agency across these chapters, I will endeavor to unfold each concept, to read the ways in which they resonate and collide to build distinct categories of physics learners.

In this chapter I formulate the theoretical framework within which I intend to operate as I analyze the data gathered from my ethnographic research, and as I write that analysis into the chapters that will follow. To build my interpretive machinery I draw on literature from a variety of fields and discourses, attempting to weave useful connections between work in educational research, theorizing in feminist and cultural studies, cognitive analyses of physics problem solving, and studies of scientific practice. I treat these literatures brutally, bending and shaping them to fit my investigative scheme; like Jerome McGann, I handle "texts as autopoietic mechanisms operating as self-generating feedback systems that cannot be separated from those who manipulate and use them." (McGann 1991, p. 15) That is, while I may employ texts against the wills of the discursive communities from which I pull them, I never employ texts against their own wills, against their own *meanings*, for texts are not things that mean, but only things that do work, and I have many jobs that need attention. I find comfort in thinking of myself as one of Edward Said's critics, who

> are not merely the alchemical translators of texts into circumstantial reality or worldliness; for they too are subject to and producers of circumstances, which are felt regardless of whatever objectivity the critic's methods possess. The point is that texts have ways of existing that even in their most rarefied form are always enmeshed in circumstance, time, place, and society - in short, they are in the world, and hence worldly. (1983, p. 35)

Because texts are worldly, not innocent, I won't feel shame as I mobilize and manipulate them in an effort to make coherent sense out of a diverse collection of literatures about learning physics.

Science Education Research: Reporting on the Shortfall

In the late 1980's many people in science and science education were concerned about the impending "shortfall" among the ranks of scientists in the decades ahead. Declining percentages of college freshmen planning to major in science and mathematics, increasing numbers of "dropouts" from the natural sciences to majors in other fields along the path to degrees, and the expectation of a continuing rise in the demand for B.S.'s and Ph.D.'s in science and engineering all appeared to point to a potential national crisis. Educators and scientists alike issued a call for recruitment of young students into the sciences. In particular, these recruiters looked to elements of the population which had traditionally been relatively untapped for scientific practitioners--in particular, women and minorities. I begin with a few studies written in the spirit of this science shortfall crisis, and note the ways that literature recasts the shortfall as, in effect, an identity crisis for physics education. From there, I will argue that from this identity crisis emerges a crisis over identity.

In a recent article in *Planning for Higher Education*, Michael Dooris documented the findings of his three week participant-observation study in an introductory physics class. Perhaps his most compelling insight was that "Physics 201 was implicitly designed for an ideal type of student: one who is focused, well prepared mathematically, and highly motivated." Similarly, in a provocative investigation of physics education, Sheila Tobias has documented the introductory college physics experiences of several students who, short of their participation in the study, were never motivated to study physics. Echoing Dooris, Tobias comments on the prototypical successful physics student:

> What we are left with after reading [the results of a survey of Ph.D. physicists] is the strong sense that scientists are born, not made. Unless they are unusually self-motivated, extraordinarily self-confident, virtually teacher- and curriculum-proof, indifferent to material outcomes, single-minded and single-track, in short, *unless they are younger versions of the scientific community itself*, many otherwise intelligent, curious, and ambitious young people have every reason to conclude that there is no place for *them* in science. (p.11) (emphasis in original)

She concludes that these students who do not choose to study physics are no less capable than those who tend more naturally toward physics, but rather that they're simply not drawn to the relatively uninspiring, unsupportive environment of introductory physics classes.

In a book titled Fear of Physics: A Guide for the Perplexed, Lawrence Krauss attempts to identify what distinguishes the physicist from the physics-phobe, and to dismantle the conceptual obstacles that separate them. He writes that "[T]he way physicists approach problems, and the language they use, is...removed from the mainstream of modern-day activity for most people. Without a common gestalt to guide the observer, the menagerie of phenomena attached to modern developments remains disconnected and intimidating. So arises the fear of physics." (1993, p.ix) To ease this fear, Krauss offers to introduce his readers to the ways physicists think, reassuring them that the "tools that guide physicists are few in number, and while it may take an advanced degree to master them, it doesn't require a massive tome to elucidate them." Summing up his project, he asks, "Is it possible for the average person to shed inhibitions, let go, and just enjoy the basic, simple pleasure of physics? I hope so." (p. xii)

I juxtapose these comments from a physicist with those of two observers of physics education in order to draw forth some critical resonances about identity. Krauss's comments spell out the cultural "differences" between physicists and "the average person" - taking shape in approaches to problems, and in ways of talking about the world - and couch those differences in naturalized terms which 'fix' their respective identities - we're *either* physicists *or* average people. Similarly, both Dooris and Tobias emphasize the distinctiveness of the physics-oriented from everyone else long before their arrival at professional physics practice. Dooris and Tobias pinpoint student identity as the key variable in predicting the success of physics education: physics curricula presuppose an ideal student who will succeed as a college physics student, and presumably continue on toward a career in the field.

But reality inevitably gets in the way; not all physics students fit this ideal mold. While physics educational discourse might replicate the same categories of identity that Krauss articulates to describe career physicists, these categories aren't sufficient to describe all the students who study physics. Introductory physics courses aren't just for future physicists; in fact, given the hordes of engineers and other science majors required to take a year of physics, the students in Foundations of Physics (the course I observed that was for physics and math majors) make up a relatively small fraction of all students in first year physics. So college physics education suffers from what amounts to an odd sort of identity crisis. By pressing a curriculum that apparently gears itself toward an "ideal student" whose place in professional physics was preordained, rather than warming up to students who might have the potential or the predilection for a career in physics but don't fit the mold, physics education only widens the gap that will grow into the impending shortfall.

Of course, in this chapter of the story about identity, 'curriculum' and 'student' are static phenomena, the one a codified algorithm through which knowledge is passed to the other. I propose an alternative model to account for the relationship between pedagogy and learning. This framework posits education as an interactive system, in which students and teacher are all actively engaged in constructing and articulating selfhood. Following a recent study of engineering education, I seek to adopt "strategies for replacing the passive experience of [education as] impact with a more active experience of agency and participation." (Downey and Lucena, 1994) But I also want to couple this reconfiguration of student experience with a parallel account of pedagogical agency, such that I might replace rigid and distinct categories of 'curriculum' and 'student' with a more holistic account of educational *process*, conceived as an interactive system. I will articulate this model more fully later in the chapter. First, perhaps taking a theoretical jump ahead of myself, I want to suggest that if the identities of students are somehow as critical to the praxis of education as is curriculum, and if the curriculum presumes a set of distinct physics-learning selves, then simply altering introductory physics curricula to reach to other students alongside the physics elect can't work. This is the "crisis of identity" I foreshadowed: physics education for "ideal" physics students, the curriculum-proof ones, and physics education for the less blessed *must be different* from one another. That is, pedagogy isn't something that exists in isolation from the students it purports to teach; it finds definition in interaction with those students, just as they formulate their academic identities through interactions with pedagogy. But to give weight to this claim, I need to more fully formulate and situate both "identity" and "pedagogy"; those will be the tasks of the second and fourth sections of this paper, respectively. Before I turn to those tasks, I want to epilogize my shortfall story.

In the years since the flurry over the shortfall, an economic recession and the end of the cold war have changed the employment picture for science dramatically. In physics, Congress's cancellation of the Superconducting Super Collider project in Texas both signaled the elimination of jobs for hundreds of physics Ph.D.'s the facility would have employed, and symbolized the end of an era of prominence for American physicists. In light of these developments, physics education may well be shoring up rather than knocking down the walls around its majors, just as professional physics is shoring up the walls between those majors and any chance of professional practice. While I can't thoroughly historicize the semester of physics I observed against introductory physics courses of years past, I can certainly note that the stark contrast between the physics of the majors course and those of the other courses, as well as the spirit of the majors course itself, all suggest a physics with little interest in inviting into its ranks just any students who might pass across its threshold.

Performing Selfhood

The previous section suggests that problematizing the limitations of tightly bounded categorizations of identity for physics students demands a critical reconceptualization of identity. For a new set of theoretical tools with which to understand the different sorts of student selves in my different physics classes, I turn now to two closely related realms of contemporary theorizing about the politics and dynamics of identity: feminist theory and cultural studies. Judith Butler has argued that "[t]here is no gender identity behind the expressions of gender...identity is performatively constituted by the very 'expressions' that are said to be its results." (Butler 1990, p. 25) Gender, then, is performance; we cannot naturalize or essentialize 'the masculine' or 'the feminine' into static categories delineated by either Nature or Culture. Identity isn't simply born, and it isn't simply made; it's performed, given meaning and definition only by the ways it manifests itself and plays itself out in the real-time of human experience. Paralleling Butler, I suggest that we cannot make sense of students' identities through essentializing categories, by simply plugging them into slots - physics major, engineering student, and so on - and assuming they either are or aren't Dooris's "ideal type of student" or Tobias's young physicist "born, not made." Rather, like Butler, I intend to theorize identity performatively, as only meaningful through enaction.

To this point I have used the term "identity" loosely, never clarifying whether I meant to refer to something inherent and definitive about an individual that remains coherent across circumstances of time, space, and community; or to a kind of academic selfhood that a student might adopt only in classroom and study surroundings; or to a stereotypical student reflected in a curriculum and in literature about physics learning. My ambiguity was intentional; I meant to invoke all three notions, for in the performative idiom they all intertwine. Academic identity is analogous to gender identity; it has no meaning beneath students' participation in the rituals of learning. And yet we can't make any sense out of an "inherent" identity or selfhood without reference to activity, to the performances of selfhood. Moreover, the stereotypes that attend my groups - physics majors, engineering majors, and life science majors - work for academic identity like masculinity and femininity for gender - they at once attempt to describe and to constrain performance.

My job as researcher, then, is to carefully observe and engage performances of student identity. Picking up a gauntlet dropped by Dorinne Kondo, I hope that

> the unity, fixity, and boundedness of the "self" can be challenged...by asking how selves in the plural are constructed variously in various situations, how these constructions can be complicated and enlivened by multiplicity and ambiguity, and how they shape, and are shaped by, relations of power. (Kondo 1990, p. 43)

In practice, this means watching the ways physics students perform different identities during lectures, while they work on homework, as they work in the lab, in interviews with me, at football games, in Squires, on the Drill field, at Arnold's, and so on, and noting the ways those performances both resonate with and resist the boxes of self-definition imposed on students by their instructors, their classmates, their roommates, the curriculum, their families, their departments, physics, and the (natural and social) world. I am not, by picking out only certain slices of these activities directly linked to learning physics, distorting an otherwise-unified picture of selfhood. There are no coherent selves which transcend situation; my view of student selfhood, like any sort of selfhood, is partial and situational.

To this point I have said very little about the role of knowledge in physics education, and yet the appearances of physics and nature in my list above are hardly accidental. I don't mean to suggest that changes in knowledge are inconsequential to learning; rather, I simply want to indicate that individual cognition comprises only one dimension of the learning process (Lave, 1988). Likewise, knowledge is not merely part of individual cognitive frameworks; in the words of Jan Nespor, in a study of undergraduate physics and management, knowledge is not "'internalized'--that is, despatialized and detemporalized," but rather embedded in the same networks of interaction in space and time as are learners and instructors (Nespor, 1994, p. 9). I will say more about this notion of the spatialization of knowledge later; for now I want to focus on its orthogonal dimension, temporality.

So what does it mean to focus on performativity in the practice of my analysis? And how do I connect these performances of self to the scripts of pedagogy, curriculum, and knowledge? In an attempt to address these questions, I have chosen to focus my analysis on problem-solving. Problem-solving is, after all, what physics students of all stripes spend a great deal of their time as physics students doing. In each of the classes I observed, not to mention in every physics class I took as an undergraduate physics major, one of the primary pedagogical tools for both instruction and evaluation was the weekly problem set. Each class devoted significant amounts of time to working through problems in class, and then expected students to solve problems on their own in homework assignments and exams. I am drawn to problem-solving as a site for comparative microanalysis for three reasons: because it has clearly defined limits--each problem has, in effect, a beginning and an end; because its temporality is particularly obvious--solving problems is a process in which students perform well-defined steps and activities; and because it couples this performativity with the knowledge-content of physics--problem-solving is the way students put to use the equations and concepts they learn in class. I intend to spend the rest of this chapter formulating the tools with which I will analyze problem-solving, and the following chapters putting those tools to work.

Problem-Solving Literature: Novices, Experts, and the Rest of Us

I'm by no means the first researcher to highlight the problem-solving activities of physics students; my database reviews pointed to mountains of literature on the topic in physics teaching and cognitive science research. To situate my approach to problem solving, I want to briefly consider three central and closely related themes that unfold from this problem-solving literature. The first describes the following pedagogical mobilization of problem-solving activity: "Teachers show students how to recognize that a new problem is like this or that familiar problem; in this introduction to the repertoire of soluble problems to be memorized, the student is taught not induction or deduction but analogic thinking."

(Traweek 1988, p. 77) On this account, problem-solving in introductory physics consists not so much of a trained and practiced algorithmic approach as a collection of problem types, and their accompanying solutions, with which students must familiarize themselves.

The second theme that stands out in physics problem-solving literature, forming the guiding topic of a huge number of articles, addresses differences between the ways "novices" and "experts" approach physics problems. Experts, generally, are trained physicists; novices are students of introductory undergraduate courses like those I studied. One researcher summarizes these differences like this:

> When confronted with a novel problem, experts typically first perform a qualitative analysis to get a sense of the type of problem with which they are dealing. The expert then applies the equations suggested by the analysis to constrain the qualitative picture and to produce a numeric solution. The novice, in contrast, tries to do a quantitative analysis first, by thinking through all the equations that could conceivably apply. Then, to sort through this welter of formulae, the novice draws on ill-developed qualitative ideas...The novice is not only trying to make the cart drive the horse, as it were, but he is also unaware of the essential features of the system: the cart's wheels, the horse's harness, and so forth. (Striley 1988, p. 7)

This expert-novice literature thus takes the analogic approach sketched above a step further, distinguishing between the ordering of steps through which these different problem-solvers reference familiar conceptual or mathematical tools.

The third approach derives from, and attempts to apply the lessons of, the second. Some of these problem-solving researchers draw parallels between the historical development of scientific knowledge, and the processes through which students acquire the same knowledge. In other words, "both the nature of the changes that need to be made in conceptual restructuring and the kinds of reasoning involved in the process of constructing a scientific representation are the same for scientists and students of science." (Nersessian 1989, p. 165) What interests me in this claim is the relationship it posits between learning and doing science, and thus between what physics students do and what physicists do. As in the case of the expert and novice problem solvers, this historical reconstruction approach makes a distinction between the ways physics students and "real physicists" do and understand physics, and recommendations are offered for making the former more closely match the latter.

I review this literature to make a straightforward point: all this problem-solving research rests firmly on the critical underlying assumption that learning physics means becoming more like physicists. But this assumption sits in stark contrast with the realities of introductory physics. Hence our identity crisis of the first section: to be a successful student, on these problem-solving research accounts, one must learn to begin performing the professional identity of a physicist. And yet that professional identity is defined and constantly reaffirmed as something far removed from the experience of students, and available to only a few select geniuses. In an analysis of undergraduate physics textbooks, Sharon Traweek argues that these texts deliver "a cluster of subliminal messages" to students, including "that science is the product of individual great men," and that, for physicists who began in other fields, "physics is of more intrinsic interest for great minds than the fields they choose to leave, such as chemistry, engineering, and history." (1988, pp. 78-79) Yet these other fields, chemistry, engineering, history, and not physics, are the ones to which most of the students I observe, most of the students who take introductory physics courses, have begun to attach their academic identities.

So again, I want to suggest that to imagine that all these students learn the same physics the same way is not only wrong, but wrongheaded. If anything is clear, it is that only a few of these students are either seeking or being allowed to foster the kind of relationship with physics that will eventually allow them to practice it professionally. Moreover, the differences among the physics-learning processes of these different categories of physics students are reflected in the different ways they learn to solve and practice solving problems, in ways more complex than expert-novice distinctions can capture. Traweek notes the work of Stephen Brush, who "has used textbooks from the Berkeley Physics Course Series to show that the students are urged to assume that they are not going to be an Einstein or Dirac, but merely soldiers in the ranks who must learn the established rules for puzzle solving [read 'problem solving'] within the existing theories." (p. 80) In the words of another researcher, "by removing physics from the realm of mathematics [reserved for physicists' understanding of the world] and moving it closer to everyday experience, [a more] qualitative approach may succeed in opening physics for the rest of us." (Striley 1988, p. 10) And even among the rest of us there are multiple ways of learning and relating to physics. Clearly, if I am to account for differences among physics education events I found in my fieldwork, I need a different way to conceptualize problem-solving than the literatures discussed here offer. With that, I make my final shift among texts, this time to the tools for theorizing the relations of knowledge, nature, and culture found at the intersection of science studies and cultural studies.

Science Studies Literature: The Mangle of Educational Practice

To build an analytical framework for his ethnographic account of undergraduate physics and management, Jan Nespor (1994) borrows from Science Studies, looking in particular to actor-network theory (Latour 1987). Similarly, I want to draw on the recent engagement of another science studies practitioner, Andrew Pickering, with actor-network theory to more clearly articulate the relationships I postulate among physics pedagogy, physics knowledge, and physics student identities (Pickering 1995). Bruno Latour's actor-network theory rests on a collection of geometric terms--networks, nodes, translations--with which it frames a spatial metaphor for the building of knowledge systems. In emphasizing the constitution of relations throughout these networks in space, Latour deliberately avoids consideration of individual points--the nodes at which actors sit--independently of the rest of the network. Because actors can be human or non-human, and because actors are defined only in relation to the network, Latour's program yields the powerful but puzzling claim that human agents are indistinguishable from non-human ones, that speaking of the goals of, say, a growth hormone is no different than speaking of the goals of a scientist.

Pickering's program, summarized in the appellation "the mangle of practice," engages this odd feature of actor-network theory by shifting emphasis from spatial metaphors to temporal ones. Hence while for Latour actors were defined by their location amid the intersecting lines of networks, for Pickering agents can only be understood performatively. While the two frameworks share many of the same features, the shift from space to time allows Pickering to tidy up the strange symmetry between human and material actors in Latour's account. For Latour, goals are defined in spatial relation to interests: "As the term 'inter-esse' indicates, 'interests' are what lie *in between* actors and their goals." (emphasis in original) (Latour 1987, p. 108) For Pickering, on the other hand, human agents are distinguished from material agents because the former have goals defined by intervals of time while the latter do not. Material agency might impact human agency just as human might impact material, but whereas the second instance might be driven by a human agent's intention to direct the interaction toward some future result (a particular experimental outcome or machine performance), the first can only emerge from the moment of a particular encounter; material agents lack the future-minded intentionality of humans.

Pickering's focus, like mine, is on performance, on interactions as well as relationships, on networks in which actors are situated temporally as well as spatially. My student-actors move back and forth across the stage and from act to act, action to action, through time. Richard White has noted that "[a]ims of students, aims of teachers, and aims of curriculum designers interact to determine what is learned" in the science classroom (1988, p. 10). While perhaps not driven by the same kinds of "aims" as White speaks of, texts, problem sets, tests, the tools and tricks of the lab, and other material agents all play roles alongside students, teachers, and curriculum designers in my identity-drama; it is partly by interacting with these material agents that students negotiate their relationships with (which is to say, 'learn') physics. So like Pickering's tales of scientific practice, my story of physics education is a mangle of interacting human and material agents. And as I try to trace their identities, I will pay close attention to their articulations of intentionality in their encounters with physics--the ways they describe why and how they go about doing (or not doing) their problem sets, reading their textbooks, taking their tests, working in their labs, interacting with their professors in and out of class, discussing their classwork with classmates and friends, and navigating course catalogs, major requirements, and registration procedures to wind up in one physics class rather than another, or any physics class at all. For the intentional structures of these actions circumscribe the contours of the students' academic selves--'why they act' connects 'how they act' to 'who they are.'

Thus Pickering's mangle of practice provides me with a way to forge my ultimate syntheses between literatures in educational research, cultural studies, and science studies. Pickering's posthumanism captures nicely the way I understand education--as interactions between teaching and learning, between curriculum and student, between pedagogy and identity--or in Pickering's terms, as the intertwined emergence of disciplinary (physics) and human (student) agency. I want to summarize the final structure of this synthesis: in order to bring into sharp focus the different categories of self introductory physics makes available to students from physics, engineering, and the life sciences, I have chosen to center my analysis on the ways students in each class are required to participate in problem-solving activities. I argue that each attempts to construct a different kind of problem-solver, a different type of student "self." Thus, engineers are problem-solvers in a very practical sense--they are being trained to solve real-world technical problems; young physicists are likewise being trained to be problem-solvers, but with a different set of goals from engineers; students in General Physics are clearly positioned as less capable problem-solvers than physics and engineering majors, and the degree to which they will succeed in their semesters in physics will depend on their ability to learn to go through the motions of problem-solving, albeit without the engineers' sense of practical achievement or the physicists' intuition about the physical situation associated with a problem. I will develop further the specifics of these differences in the chapters to come; for now I want to stress that I find this emphasis on problem-solving particularly useful because it facilitates connections between selfhood and the physics "content" of the courses.

Having sketched the lines of such connections, I turn back to Pickering for a way to articulate the real-time interactions of these student and disciplinary agencies. When physics students work on problem sets, they must, like William Rowan Hamilton in Pickering's example of the formulation of quaternions, observe and contend with "particular routinized ways of connecting marks and symbols with one another" (1995, p. 115)--the equations of motion, the rules of algebra, and so forth. On Pickering's account of mathematical problem-solving practice, agency dances back and forth between the mathematician and the mathematics. At one moment, the mathematician is actively making "bridging and filling" moves--creative moves like the analogic and qualitative reasoning we saw encouraged in the physics problem-solving literature. In the next instant, however, the mathematician is working out the routine steps of translating numbers across the conceptual bridge established by the previous moves. In these steps, "scientists become passive in the face of their training and established procedures." (p. 116) Mathematical work, then, and likewise physics problem-solving, can be understood as arising from this interplay between human and disciplinary agency.[2]

Following this line of thought, I take a logical step further. I have said that I conceptualize "education" as emergent from the interplay between curriculum and students. I contend that in each class these problem-solving activities occur differently--the same concepts and the same problem topics produce entirely different solving events. And these different problem-solving events follow directly both from the different pedagogical aims, mathematical resources, and problem organizations (each of which I categorize as manifestations of disciplinary agency) associated with work in each class, and from the

[2]It might seem odd that I have chosen Pickering's lone example drawn from the practice of mathematics, rather than one of many drawn from physics practice. But there is an important difference between the practice of 'real' professional physicists and that of my students. The activities of undergraduate physics students center around problem sets, exams, and lecture notes, not accelerators, detectors, telescopes, and so forth--the tools of the large scale practice of professional physics. The mathematical practices Pickering traces are in fact much closer to students' problem-solving practices than are his physics examples.

different intentional agencies and mathematical skills that students with the goals specific to their academic trajectories bring to their study of physics and their solving of physics problems. To put it even more contentiously, I claim that each of these classes deals with a different physics, because the physics of each class takes shape in tandem with the different groups of students who study it. In the chapters ahead I will concern myself principally with outlining the different disciplinary agencies of each class, the different student agencies of each class, and the consequences of their interactions.

Chapter 2
Diagramming the Problem: The Force of Curricular Structure

Last spring, when people asked me what my thesis was going to be about, I had a game I liked to play as a response. I'd ask them to match the titles of four different introductory courses, namely "Principles of Physics", "Elements of Physics", "Foundations of Physics", and "General Physics", with the majors of students for whom they were designed: physics and math majors, engineering majors, other student majors who had studied or were studying calculus, and other student majors without calculus, respectively. The majority of the people I asked quickly realized that Foundations must be for those in physics and math, Principles was for engineers, Elements was for other students who had had calculus, and General for other students without calculus. Those who had any difficulty making all the matches were invariably the people who gave their answers the most thought, and who were already most familiar with the curricular structure of physics or engineering at this university.

So my game really depended on quick responses, on matching words with stereotypes. To play successfully, respondents needed to call upon their familiarity with assumptions and generalizations about various kinds of students, and about the different relationships they knew each kind of student should have with an introductory physics course. They knew that physicists need solid foundations on which to build their future acquisitions of knowledge, that engineers need to have all their principles down so they can put them to good use, that other students seeking to learn physics are free to simply explore the general scope of the field, and that those who have sufficient mathematical skill and scientific aptitude can even appreciate some of the fundamental elements of the field.

"Elements of Physics" was not offered during the semester I conducted my research, but the differences between the "Elements" and "General" curricula and intended audiences are less dramatic then among the other courses. Both are defined by the university's undergraduate course catalog in opposition to the physics and engineering courses. Elements of Physics is "For students in curricula other than physical sciences, mathematics, or engineering, who have studied calculus at the level of college mathematics"; General Physics is "For students in curricula other than physical sciences, mathematics, or engineering, who have not studied calculus." So these descriptions indicate that the only significant difference between the courses is that one presumes familiarity with calculus and the other does not. But I want to stress that the lines between these courses are blurrier than the catalog suggests. I first discovered these ambiguities in an interview with a student in the General class. Curtis, a geochemistry major, had studied far more math than his physics sequence expected of him, yet he still lacked the mobility to take a different course:[3]

Toby: OK. What's your math background? Have you taken...

Curtis: I've taken calculus.

T: You have taken calculus.

C: And I'm taking linear algebra now, I don't know how much that plays into...

T: Huh, yeah. So you could then have taken [Foundations of Physics].

C: Uh, no. Actually, I took [calculus sequence number]. It's not the engineering sequence of calculus; it's another one for, I believe life sciences and stuff. And I...for geology that's all that's required. And then I decided to go for the option of geochemistry. And the...whatever the engineering calculus is required for that, but they waived it for me since I'd already completed the other calculus.

I soon learned that many of the students in the General Physics class have taken some sort of calculus, but either they didn't take the appropriate math for a calculus-based physics course, or they didn't need to take a calculus-based physics course to meet the requirements of their own major curriculum. I want to draw two points from this story: one, that the differences between the General and Elements classes are less sharp than among the other classes, and so investigating three rather than all four courses didn't limit the scope of my study; and two, that the distinctions among students in each class made by the course

[3]All names of professors and students are pseudonyms

catalog and the real experiences of students are often a poor match. I will take up this second point in greater detail in the third chapter; for now, I want to more thoroughly map out the differences among the courses and their students as understood from the vantage point of the curriculum and its implementers.

I began each of my interviews with physics professors by telling them that I was intrigued by the number of different introductory courses the department offered, and that my project was about comparing the courses to plot the different trajectories of different groups of students through physics. Invariably, the professors responded by downplaying the significance of those differences, and stressed that the only differences were in the math background students were expected to bring to each course. According to Dr. Smith, the instructor of Foundations of Physics,

> ...the general goal is to try to get the students to look at the world the way that physicists look at the world, which is to say that you see patterns, and you try to organize those patterns into as simple and as precise as possible a description as you can. And invariably that description is mathematical...the introductory-level courses all have pretty much the same syllabus, in fact, if you look at the content of the courses, I believe until very recently, they've all been roughly organized along the same lines, material presented in the same sequence, even...we start off with things that students should be comfortable with at least observing or feeling or whatever, without necessarily knowing how to describe it in this precise language of mathematics. So then you say, well, why do you have this differentiation through the three sequences. And it basically comes about from our recognition that the students come in with a very wide range of preparations in terms of math. So the curriculum is then at that point split up to acknowledge this fact, that there are some students who come in with very, very rudimentary training in mathematics, to the other end of the range where you have students who have a lot of calculus and algebra and so on, are completely comfortable with this more formal kind of mathematics that you need in order to describe the physics again, more concisely. And then the engineering students are somewhere in between. So that's why we have three different sections. But in all cases, the idea is to try to get those students to think about what they see and observe and what's going on, try to classify it, and in as many places as possible, classify it quantitatively, using the language of mathematics.

So Dr. Smith recognizes that the students who take introductory physics at this university have widely varying degrees of familiarity with math, and he conceptualizes both the students' levels of preparation and the design of the courses along a range of mathematical sophistication. Math backgrounds aside, though, he stresses that all of the classes address basically the same material, and concern themselves fundamentally with teaching the students to see the world the way physicists do.

In contrast to the professors' emphasis on math training as the determinant of a student's introductory physics course, the course catalog appears to tell an alternative story. Therein, Principles of Physics is described as being "For students in engineering," and Foundations of physics "for students in physical sciences and mathematics." Unlike the General Physics and Elements of Physics course descriptions, these summaries don't mention calculus explicitly, but rather differentiate among the students by reference to their major departments. In all cases these classes are demarcated not by their content, not by the physics they deal with, but by the student audiences to whom they address themselves.

In this chapter, I argue that the superficial and stereotypical ideas about different sets of students that I began with reflect and resonate with deep and important differences in the curricular structure of the classes. Each class is a distinct field of activities and meanings, each makes a different set of assumptions about its students, and each outlines a different pattern for successful student performance. More importantly, these differences are *structurally similar* at each level--whether I cast them as unique performative and interactive events, or the course catalog casts them as attending to the distinctive needs of students from different majors, or the professors cast them as accommodating the diverse mathematical backgrounds of their students, we are tracing the same boundaries, reinscribing the same dividing lines among students and their experiences of physics.

Foundations of Physics: What Better to Build a Career on?

When I asked one of the physics majors I interviewed if he was enjoying his introductory physics class, I received an intriguing reply. Rather than address my question directly, he responded by offering an evaluation of the professor: "Um-hm. I like the professor a lot, he's a very...very good physicist, so I think he's a very good teacher." It struck me as odd and a little funny that the student thought being a good teacher followed from being a good physicist, but I let the discussion shift to focus on the class. As the interview went on, though, and I listened to the way the student talked about his love for physics, his reverence for the "great physicists"--Einstein, Lawrence, Feynman, his approval when I told him I had been an undergraduate physics major (he gave me a thumbs-up and said "All right!"), I began to understand the logic of his physicist-physics teacher equation. As a physics major with aspirations of a career in the field, his central concern was with becoming like his professor, and so the most important thing that professor could do in class and out to instruct the student was to model the behavior of a good physicist.

Sharon Traweek (1988) describes the training of a physicist as a "Pilgrim's Progress" through undergraduate, graduate, and postdoctoral work, in which the "physics community renews itself by training novices." (p74) Students begin by being taught to revere the heroes of physics, and to recognize "that there is a great gap between [those heroes] and their own limited capacities." (p75) To complete the long journey toward a successful career in physics, students have to slowly but steadily narrow that gap, molding themselves into members of, and thus replicating, the physics community. Through my fieldwork, I came to understand the class for physics majors as fundamentally devoted not simply to teaching physics, but to teaching students how to perform as physicists.

Of course, this doesn't mean the students learned how to *do* physics. Students are typically well into graduate school before they begin to take part in the research activities and laboratory activities of full-fledged physicists. But the professor nonetheless drew a clear connection between the skills he hoped his students would develop through their class exercises and those skills they would need to draw on if they became professional physicists. In the interview excerpt at the beginning of this chapter, Dr. Smith started his overview of the introductory sequences by pointing out that in all the courses, "...the general goal is to try to get the students to look at the world the way that physicists look at the world." In the next two sections of this chapter I will question the aptness of that description for general and engineering physics, but here I want to stress its success in accounting for the activities in Foundations of Physics. Of course, it's not a perfect description of what students in the class really spend time doing; after all, students in an introductory physics class spend little or no time actually looking at the world. Rather, they spend virtually all of their classroom time solving problems--either working their own homework problems, studying problem solutions before or solving problems during a test, or following along as the professor or the textbook leads them through the strategic and conceptual steps of a problem. And seeing the world as a physicist does means seeing, and solving, a problem the way a physicist does.

Trying to ferret out the unique features of his class from his uniform picture of the general goals of all the introductory sequences, I asked the Dr. Smith what a student had to do to be successful in his class, and who his class was designed for. He stressed that his focus was on encouraging in his students the style of working and thinking that he believed would best prepare them to do research in the physical sciences, freely admitting that this focus did not match the professional futures of most of the students:

Dr. Smith: My course is designed for someone who is going to end up doing research in physical science. Not necessarily in physics, but for someone who's going to have that, I think, as their ultimate end. It certainly doesn't match most of the students who take the course. I mean, if you look at where they end up, very few of them end up in a role that's like that. But that's I think what the course is designed for, is for someone who's going to be, as a professional, involved in some way in doing research, either with a university, or in a company, or with the government, somewhere else, but a researcher in physical science. that's, I believe, I mean that's what I think of with the students that I see--that they're going to end up being somewhere, doing something like that. Whether it's in chemistry or biology or physics or...engineering, wherever. That they're going to end up looking, they're going to end up doing research, and I would like them to be able to, when they're doing their research, to look at a problem in the way that I would.

Toby: And how is that?

Dr. S: Well, just to try to attack it from, first from a big picture point of view, first to try to see what are the essential features of the problem, to try to learn how to throw out all the non-essential things first. I mean eventually it'll all have to come back in, but to see it first of all as simply as possible, and try to analyze it numerically, because it's mathematically important, and then once you have a gut feeling on that scale of how things work, then you can start bringing in slowly one complication after another, and then come to compute and understand what's going on.

This "big picture" approach provides the key to understanding the way physics majors are being forged into physicists, into a different kind of problem-solver from the non-major students who take an introductory course. The campus bookstores at the university that hosted my research each stock several copies of a collection of physics problems generated by the Physics Department at the University of Bristol, published under the particularly catchy title "Thinking Like a Physicist." The editor stresses in the introduction the desire he shared with his colleagues to "encourage" in his own university physics majors "the cultivation of a group of skills which we regarded as an important constituent of the expertise of the professional physicist." The items at the top of this list of skills are strikingly similar to those offered up by Dr. Smith: "the ability to convert a 'real' problem into a 'model' that is susceptible of quantitative analysis, by extracting the essential elements; to analyze the behaviour of the model, making whatever approximations are necessary, and to be aware of the consequences of these approximations." (Thompson 1987, v) Physicists see problems, and want their students to see problems "as simply as possible," in terms of mathematical models and approximations. After all, the real world isn't at stake when a physics student, or even a physicist under most circumstances, solves a problem; what is at stake are concepts, theories, general ideas about how the world works.

"Thinking Like a Physicist" goes on to distinguish between two general types of physics problems--"the 'well defined' and the 'open-ended.'" While the author doesn't dismiss "well defined" questions, which have a clear answer, he is primarily concerned with "the type of question in which the emphasis is on ideas, physical intuition or creative thinking...There is no 'right' answer; indeed, there may be no answer at all. It was of this type that one of our colleagues once said 'I don't know the answer--but I am sure that I can distinguish a good attempt from a poor one.'" Problems such as these "call for the deployment of intellectual skills that play only a small part in traditional written degree examinations, yet which are of prime importance in terms of the ability of a physicist to 'do' physics in the real world." (Thompson 1987, vi)

Thus the sort of problem-solving these physicists engage in as the work of their profession, and the sort of work they want to encourage their students to learn to do and to learn from doing, emphasizes the process of solving a problem rather than the result of that process, the solution. My conversation about problem-solving with Dr. Smith continued in this vein:

Toby: So it's very different from, I mean it's not just a goal-oriented approach. It's not just about what's going to be the solution. It's...

Dr. Smith: It's to see how things work.

T: So it's, yeah, OK. It's making connections between the problem, the issues at stake, with the concepts.

Dr. S: Right. I mean the goal is a nice thing to eventually reach, but in fact, the whole process of going from, starting on a problem and actually ending up is so satisfying. I mean, that's what I think students should learn to appreciate. And that what I think I'm trying to convey, is that although we just do problems at the blackboard and stuff like that at this point, they do a few things in the lab to try to see...but the idea of just starting with something, thinking about it, puzzling about it, and then working your way through to the end, that whole process of working through, is they learn to see that's enjoyable. That's what I try to get across.

Again, Dr. Smith wants the students to take from their encounters with problem-solving an appreciation of that activity as a process in itself, not simply a route to a result. This emphasis on process rather than solution will become particularly significant when we compare it to the activities of the engineering and general physics students in the next sections. For the moment, though, I want simply to establish an image of the physics problem-solver-in-training. These physics majors are encouraged to be independent, creative thinkers, to develop their intuitive grasp of physical situations, to solve problems by feel and instinct rather than rule or method:

Toby: Sure. So you're trying to teach them to solve...to, say approach a problem...You're trying to give them a heuristic rather than an algorithm--you're not trying to take them step-by-step...

Dr. Smith: Yeah. I don't like to give them an algorithm. I mean, very often, students ask, especially engineering students, would say, "write down the procedure for me, and I'll know how to do that task." And I try, even when I taught engineering students, I would shy away from trying to do that. I would try to say, "think about what's going on, and just see if you can connect it to everything that you've learned. And make your own procedure."

This anecdotal reference to engineering students underscores Dr. Smith's understanding of both those students and the physics majors. By emphasizing the tendency of engineering students to request rules and steps to follow in the problem-solving process, he suggests that there is something different about each set of students, prior to his teaching them, that manifests itself in the way they feel comfortable and confident approaching problems. By stressing that he used this approach "even" with the engineering students, he indicates that the problem-solving style he wants all his students to develop runs particularly counter to the style he associates with engineers. We continued:

Toby: Yeah, so tell me more about that. What strategies do you employ to help students to pick up those, your approach to a problem?

Dr. Smith: (pause) That's hard to say. It's really case-by-case. I don't have any set strategies that I know of consciously. I pose a problem, or have them pose a problem, and then I just, I have them watch me work it out in real time.

T: So it's something you model?

Dr. S.: And I try to explain what I'm doing as I'm working it out. I don't actually have...maybe there is, maybe I do actually, if students say, "well this is what he's doing, he's always doing the same thing over and over again, he's got a pattern," but I don't see it that way. Maybe there is a pattern, but I don't see it that way.

So Dr. Smith teaches his students how to solve problems as a physicist would, teaches them to think like physicists, teaches them to approach a problem as he would, by performing his own approach in front of the class. For him, teaching the approach eludes specific articulation; he finds it "hard to say" what he does to teach his problem-solving style, and he doesn't have any strategies that he "know[s] of consciously." He simply starts into a problem, and has the students "watch me work it out in real time," explaining his actions as he moves along. He can only describe the process of teaching problem-solving by recourse to the performative idiom. Becoming a physicist involves not simply the mastery of a set of concepts or a body of knowledge, but rather the more intricate mastery of a way of thinking, of behaving, of looking at the world. Physics professors transmit these skills to their successors not by handing them rules, steps, or procedures, but by demonstrating those skills in action, by modeling in real time the activities in which the students must learn to engage by practicing those skills and activities themselves.

What did this modeling really look like? This segment of a class transcript shows this same professor, Dr. Smith, in front of his Foundations of Physics class, performing the process he had described to me in the interview:

If you're not aware, we've now finished chapter 4, and we'll talk about things in chapter 5 today. But one of the students told me that it would be nice to go over problem 38 from chapter 3. I will give you some idea of how I would think a problem through at least, not to say that this is the only way to think a problem through, because I'll show you the three different ways that you could have presented this solution. I intend just to give you an idea of the kind of logic that, to practice wouldn't hurt you. So these problems are assigned with the idea that you practice going through the techniques, and also trying to develop your intuition. Remember the last time we had the question about your intuition about what happened on the homework. Well, you have, let's say, a sufficiently developed intuition about it, as most of you did, then you would know that the moon exerts gravity just like any other mass, a massive object exerts gravity, and will pull inexorably on the pen, and on the astronaut, and on anything else that has mass near the surface of the moon. So anything with mass on the surface of the moon will fall. It just happens that the moon, not being as big as the earth, will not pull quite so hard on the pen, or an astronaut, or whatever. But it will pull. OK, so what we're going to keep doing is hammering home some of theses ideas that hopefully you'll be able to come out of the course with. So some of the students that have come to see me out of the lecture have expressed some confusion about the massive number of formulas we keep seeing in this textbook. There's a tremendous number of formulas. But I think the ones that you should try to keep in mind...but for now the main formula that you want to remember is Newton's second law.

The instructor here explicitly displays the teaching strategies he told me about, telling the students he is going to "give you some idea of how I would think a problem through." He does, of course, assure the students that he doesn't mean "to say that this is the only way to think a problem through," and he goes on to show the students three alternative paths to the problem's solution--his way, the textbook's way, and his grader's way. But the differences among these approaches amount to variations in mathematical formulation at the end of the problem; Dr. Smith showed these variations only after he had already shown the students how he would frame the problem conceptually, how to understand the problem in terms of Newton's second law. All the approaches started from the same emphasis upon "the kind of logic that, to practice wouldn't hurt you."

To ground this "kind of logic" before moving on to the actual solutions, Dr. Smith demonstrates the kind of physical intuition students should be developing at this point from their familiarity with Newton's second law. Setting the standard for conceptual insight the students should have achieved by this point in the course, he tells the students that if they have "a sufficiently developed intuition about it, as most of you did, then you would know..." Dr. Smith thus spells out the particular kind of sense the students should be developing about this physical scenario--a sense that hinges not on experiences of the world they might have had prior to their encounters with physics, but on Newton's formulation that Force equals mass times acceleration. The students don't, any more than the rest of us, feel the gravitational pull that their pens, or that they, exert on the Earth; the acceleration due to that force is far too small to draw notice within the realm of our physical experience. But if they've learned their dynamics, and if they really understand not only how to manipulate the equations, but how to make sense of those equations physically, then they should be able to make sense of the equivalence between the product of their own mass and their acceleration due to the Earth's gravitational pull, and the product of the earth's mass and its acceleration due to their gravitational pull.

Principles of Physics: What Better to Build Bridges on?

In one of the first meetings of Foundations of Physics, Dr. Smith spelled out some of the key difference between his physics students and the stereotypical engineer. When a student raised his hand at the start of class and asked about the structure of the exams in the class, Dr. Smith assured him that there were no multiple choice tests in the course, and that the tests would be graded for reasoning as well as right answers. He then continued, "If this were an engineering course, a wrong answer would be a zero, because engineers build bridges, and wrong answers mean bridges fall down." Another day, while the professor was working through a problem, a student pointed out a mistake:

Dr. Smith: ...The y-component is plus T(3)cosine(alpha) and minus T(1).

Student: Shouldn't that be sine?

Dr. S.: ahh...the cosine should...oh I have them backwards, right, because I have alpha over here. You're absolutely right. I kept thinking alpha...you're right...I would fail as an engineer. You have to keep track of all these nitty gritties.

Once again, then, the different identities that Dr. Smith associates with physics students and engineering students hinge on differing approaches to solving problems. On this account, engineers concern themselves primarily with the real world; the principles they draw on, the computations they do, and the problems they solve all have consequences outside the classroom. This accountability to the real-world results of their work forces them to be attentive to detail--or perhaps their attentiveness to detail draws them to engineering. Unlike the physics majors, who are learning to be creative and intuitive problem-solvers, to develop their physical intuition, and to concern themselves more with general frameworks and concepts, and with the process of problem-solving for it's own sake, engineering students have no time for conceptual feel and mathematical elegance. Rather, engineering students solve problems in order to achieve a solution. I first began to realize this difference on a day when I attended Foundations of Physics and then Principles of Physics back-to-back. In the majors' class, Dr. Smith spent the entire hour working through the various components and conceptual dimensions of a single example. In the engineering physics class, however, the professor, Dr. Davis, set up and quickly discussed 7 different problems, often only working them to the point where one would only need to plug in numbers and compute the result, and then leaving the students to do the rest on their own.

Dr. Smith's frequent in-class references to the differences between himself and engineers are neither typical nor trivial physics-talk; rather, they stem from the particular institutional location of the physics department I studied. Situated in a large polytechnic institute and state university where the college of engineering boasts a large share of the school's enrollment and resources, the physics department suffers the inconvenience of sharing authority over knowledge about the physical world with another, more powerful program on the same campus. Because both the materials that the physics and engineering departments want their first- and second-year students to cover, and the abilities of the instructors in each department to teach those materials, frequently overlap, the programs find themselves vying for students and other resources. The professor I interviewed, who was preparing to retire after an entire career spent teaching the introductory engineering sequence, expressed his frustration at the interdepartmental politics associated with the course:

Dr. Davis: And furthermore, I mean, you're kind of (pauses)...since I'm laying all these grievances out, I mean, I'm going to go out the door, so I may as well speak my case. That is that for 30 years, I've been here for 30 years, 29 years, and for 30 years, we've been fighting this same battle. And that is how do improve or make better the engineering sequence that we teach. We get a lot of students in this sequence. And over the years we've tried a variety of things, but the bottom line is always the fact, is *always* the fact that we shove material at them in these three hours that they give us, that there's no decent way to go through it and have it properly register. The only way to cure this course, in the long run, is to allow more time to teach it. And that's something that has been a big political struggle between the physics department and the engineering sequence. You see, the politics of the university is that faculty sizes are allocated on the basis of student loads. And so they fight tooth and nail to retain as much student load as they can, particularly at the undergraduate levels, because there you can pack 'em into large courses, and do it very efficiently, so there's been this political struggle between engineering and physics over the years, and we've never managed to get an additional hour to teach this course. And it's been my particular opinion that this course is never going to amount to a hill of beans until that's done. There's no way to cover the breadth of material that we do. You're always going to get complaints, the students are always going to think that you're moving too fast, you're under a mandate to cover the syllabus, you have to go through this material, and I just don't see any way to do it without more time being put into it. And apparently that's not going to happen. That's why this thing was worked out with the engineers. They were reluctant to give us the time required to do a full teaching of the course, so they said, well, we'll teach aspects and we'll teach pieces of it. And you can concentrate more in modern physics, which is a good idea. But what that ends up doing is that we have to assume that they've been given the proper training and education in the mechanics that we're going to use throughout the rest of the course. And I don't think that that's, I don't think that that's a provable thesis, at least not in my experience. So this has been going on for 30 years. At one time, in fact, the engineers managed to get the mechanics entirely away from the physics department, and then this got to be a big, even a university struggle, and they...I think they ought to look around at what our peer institutions are doing. And this university, in teaching just three lecture hours a semester for two semesters, that's the basic physics course that we give the engineers, is I think running behind the national norms. Most of the people I talk to at peer institutions, you know, are doing engineering as maybe 3 hours of lecture and an hour of recitation, and perhaps they have a lab associated with this, or maybe even four hours of lecturing and stuff. So I think that we're behind in time that we give to teaching these engineers, according to our peer institutions.

This rich account of institutional history reveals critical contextual issues at stake in the courses I investigated. The tensions between the departments have a polarizing effect; the physics professors constantly distinguish between their way of doing things and the engineers'. Each time they do so, they sharpen the divide between the engineering students and their own majors. They reinforce the idea that an engineering curriculum attracts and produces one kind of student, the physics department quite another. In the next chapter, I will examine some of the consequences of this differentiation for students; for now I want to examine more closely the ways the professors and the curriculum police the walls between the programs and the students.

I have been insisting throughout this work that the different presumed and desired student types of these classes correspond to differences in the ways students engage in and are instructed in cognitive activities. Following up his story about departmental struggles over who taught what, I asked about the possible implications of who taught a particular set of concepts for the manner in which the material was taught:

Toby: Do you have sense that when you're struggling over who's teaching these sections of things, who's teaching mechanics and so forth, do you think the engineering department is doing something different in its presentation of mechanics, or is it just the amount of time spent on it?

Dr. Davis: No, it's just...I'm not quite sure how to answer that problem. We have different ways of doing things between the two departments, I mean we try to unify, and I think they've come along way in that regard, try to unify notations and so forth. I mean, it used to be considerably worse than it is now, just notational things. But if I want to show a student for example that magnetic forces, that there are constants in the motion of a magnetic field, one being the velocity squared, the velocity because it's a tangential...it's a normal force, if I want to show that, you know, if I do it, I have confidence that at least they've seen it, they know it, and that's the case. But I'm not at all confident that they have that information from the engineering training that they're getting. I think that the concentration in the engineering tends to be more static situations, it's just a different emphasis in things. So we use as examples, for example the mechanics, you know, particle dynamics a great deal. And I don't think they tend to do that over there. Anyhow, I'm just spouting off. (laughs)

Dr. Davis's reference to the different emphases of the departments--the physicists' interest in systems in motion and the engineers' focus on static situations, was echoed by Dr. Smith one day in Foundations of Physics. Showing the students some examples from statics, the professor demonstrated the significance of the material by discussing its importance in engineering:

Dr. Smith: "So statics is a practical course. They have an entire course here in the engineering school, devoted just to this subject. This is not a trivial case. This is a practical force. And statics, in fact, doesn't cover just the statics that we're going to talk about today. So you might say why have a whole course on statics? Well, statics covers more than just the equilibrium that we're concerned with here, namely an equilibrium (...) translation. When you later get to rotational motion, you also want to worry about rotational...So you put all those things together, and you can imagine going through enough examples of bridges not falling down, or diving boards extending out without cracking, and things like that, that you can imagine having the necessity for dealing with the practical problems of statics. In fact, one, or the professor I guess, who does a lot of lecturing on statics got some big award last year from the university for his excellence in teaching this particular subject matter, and this year was given an endowed chair. So it's something that's well recognized and of importance in this university and everywhere."

Dr. Smith's hypothetical query, "why have a course on statics," wasn't offered up by any of the students. Rather, Dr. Smith assumed, prior to any student expressions of concern, that he might need to justify spending time on the material. His invitation to the students to "imagine going through enough examples of bridges not falling down, or diving boards extending out without cracking, and things like that" encapsulates his ideas about the issues and situations that are of interest to engineers.

This was not the only time Dr. Smith made references to the other places students might encounter a given topic in another course. He spoke about this strategy in our interview, after I asked about different things he did in teaching the engineering and majors' sequences (unlike many of the physics faculty who had come to specialize in teaching only one of the introductory sequences, he had taught both of these):

Dr. Smith: Hmmm. Well, certainly when I teach the course, when I teach [Foundations of Physics], I quite often refer to the fact that students who will continue in physics will get to see certain things fleshed out in a lot more detail, whereas I know that if

I'm teaching [Principles of Physics], and I suspect that other people do the same thing, know that that's the last time the students will ever see physics. And if something doesn't get covered then, or if it's glossed over, or whatever, there's no opportunity to come back to it again, to revisit it. It's there and it's gone. So it certainly affects the way that I actually implement...the way I teach the course. If I have some suspicion that students will be coming back to something again, in later studies, then if I knew this was the one time they were going to see lenses, or other things in optics, what they hear from me today is the last they're going to hear about it, unless they put a pair of glasses on or something, but then they won't think about it, either.

Toby: (laughs) Right.

Dr. S: But I see that more like a detail, not...I mean, I like to look at things far away, the big picture, and then there are fine points. I consider that a fine point.

So the professor works from the assumption that his Foundations of Physics students will likely take a great deal more physics after this course, and perhaps even spend their careers doing physics. For these students, he is free to constantly point ahead, to make reference to what the students will do in future semesters. This, after all, is how physics curricula are structured--a student meets most of the concepts she will study as an undergraduate in her first year of physics classes, and subsequent courses at the undergraduate and even graduate level will focus on developing those concepts in increasingly sophisticated detail.

The "pointing ahead" strategy in the first-year sequence reflects two of the assumptions from the last section that beginning majors encounter in physics, namely that there is a great distance between what they do now and what more advanced students or real physicists do, and that they have the freedom and the intellectual capacity to take their time in their courses to build physical intuition and conceptual and mathematical sophistication. Engineering students, on the other hand, will only have one pass through this material--or at least only one pass taught to them by physicists, and they must make the most of it. More to the point, though, I want to suggest that this distinction follows from the different relationships physics majors and engineering majors are allowed to have with physics. The next excerpt from a Foundations of Physics lecture delineates this distinction between student committed to long-term physics study and practice, and those who are just passing through:

Dr. Smith: The book makes this big point about the fact that anyone who deals with physics always starts off by drawing free-body diagrams. Well, I never draw free-body diagrams, because in fact, once you get beyond this level of Newtonian mechanics that we're talking about in this course, you don't even talk about forces. Force is, in some sense, an anachronism. It's a very practical thing to deal with, let's say, from an engineering point of view, it's of value, because it's useful. But when you go further on in physics, you're taking mechanics now, but if you were to take another mechanics course again, you'll very rarely hear the word force. You'll hear about potentials instead. So the statement that the book makes about every physicist always starting off by going through free-body diagrams, you can't accept that. It doesn't work that way. [pauses, then, almost as an afterthought:] But, for you, you should draw free-body diagrams. It's good for *you* to do it. It's a good way to start thinking. But in the end, if you continue on in physics, the concept of free...you always have them here, but in other kinds of contexts, force tends to be left aside for more useful kinds of mathematics. Like tension, we won't talk about tension, we'll talk about force. OK, so there are the four forces, of which only two you'll see here, and you'll see them in somewhat mysterious form...

Here, Dr. Smith distinguishes between the respective future interactions physics and engineering students will have with mechanics. Physics majors should practice drawing free-body diagrams now, because "It's good for *you* to do it. It's a good way to start thinking." They aren't practicing them so that they'll graduate as excellent free-body diagram artists; in fact, by the time they've graduated, they'll have seen more sophisticated descriptions of dynamics that render free body diagrams and the forces they represent anachronistic. They're drawing them in order to attain conceptual benefits, to develop a sense of the kinds of models that they can draw on to conceptualize physical situations. Furthermore, what they do glimpse now will be shrouded in mystery, hidden beneath veils of mystical secrecy which they might remove one-by-one as they acquire more sophisticated mathematical tools. Engineering students, on the other hand, will never see more complex mathematical models of these situations. But this inequity doesn't simply follow from the amount of physics each group of students will be fortunate enough to study. Rather, engineering students will mobilize the knowledge they acquire in different ways than will the physics majors. Dr. Smith stresses that the concept of force is "a very practical thing to deal with, let's say, from an engineering point of view, it's of value, because it's useful." Engineers, then, should only concern themselves with practical, useful knowledge, even though physicists might have more powerful and sophisticated formulations of the same physical phenomena. Engineering students must learn that they only have access to the principles of physics so far as they can draw on that knowledge to do engineering work, to make bridges stand up; they will never probe the more fundamental secrets of the universe that are reserved for real physicists.

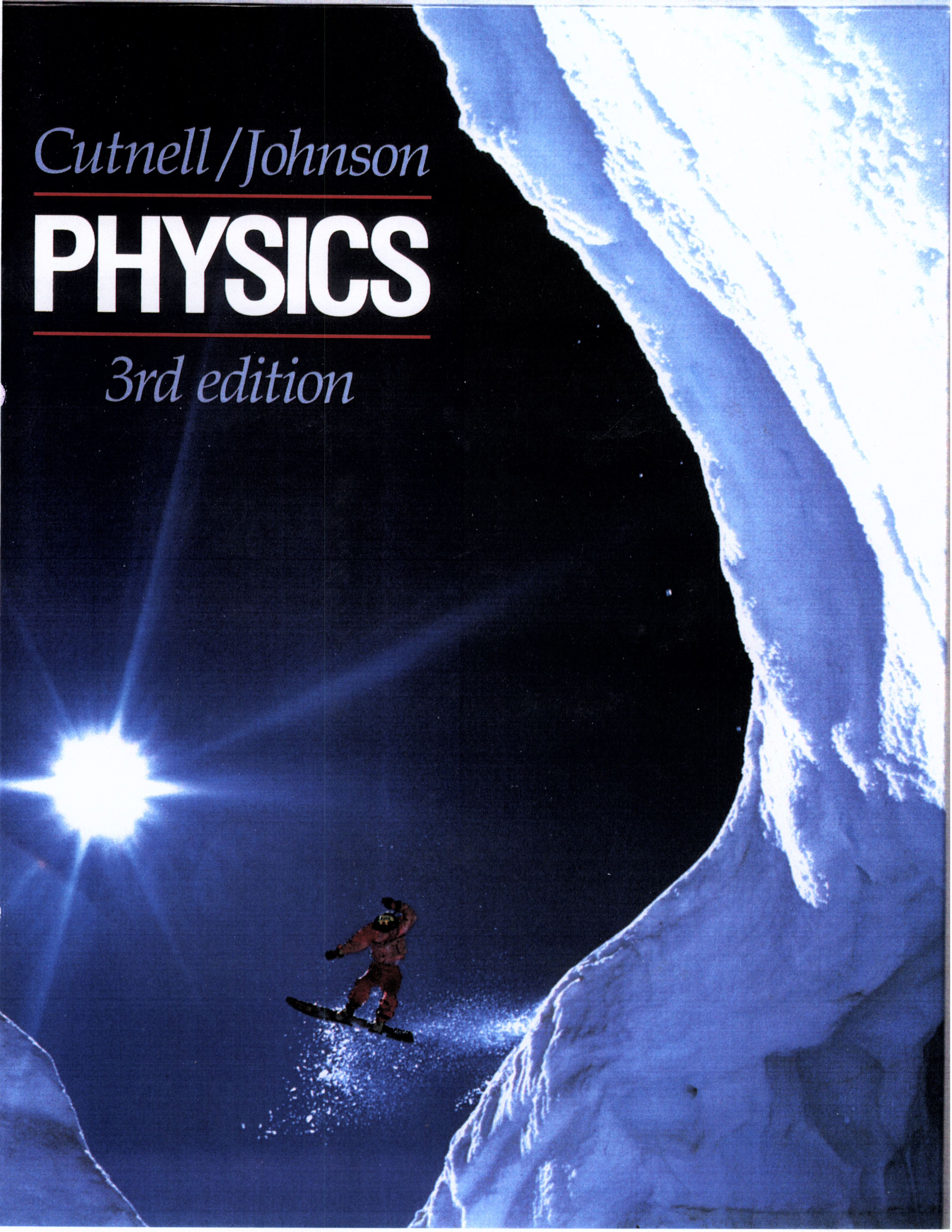
General Physics: Novitiate Negotiations

The cover of the textbook for General Physics looks more like something one might find on a poster in a thrill-seeking college student's dorm room than on the front of an instructional handbook. The picture shows the small red-suited figure of an airborne snow boarder performing a dramatic maneuver against a backdrop of powdery snow cliffs, glistening sun, and deep blue sky. Comparisons with the covers of the texts for the other courses reveal a great deal about the differences among the courses, and among the students who are expected to take them (see accompanying illustrations). The book for Foundations of Physics also bears an action-photo on the cover, this one a group of blurry bike-racers speeding around a curve. But quite unlike the picture on the General physics text, this photograph is marked for physics analysis. Superimposed on the picture are a collection of blue, purple, and green vector arrows marking the forces working for and against the lead bike racer, each appropriately labeled as the force due to friction, the normal force, the force due to gravity, and so on. Inside the book, there is a smaller version of the same photo, and underneath it a paragraph explaining these forces and the ways they combine to produce the final motion of the cyclist. By further contrast, the cover of the engineering physics text had no photograph at all but rather a blue-and-black sketched drawing of some sort of antiquated mechanical contraption, complete with gears, screws, belts, and assorted other moving parts.

Cutnell / Johnson

PHYSICS

3rd edition



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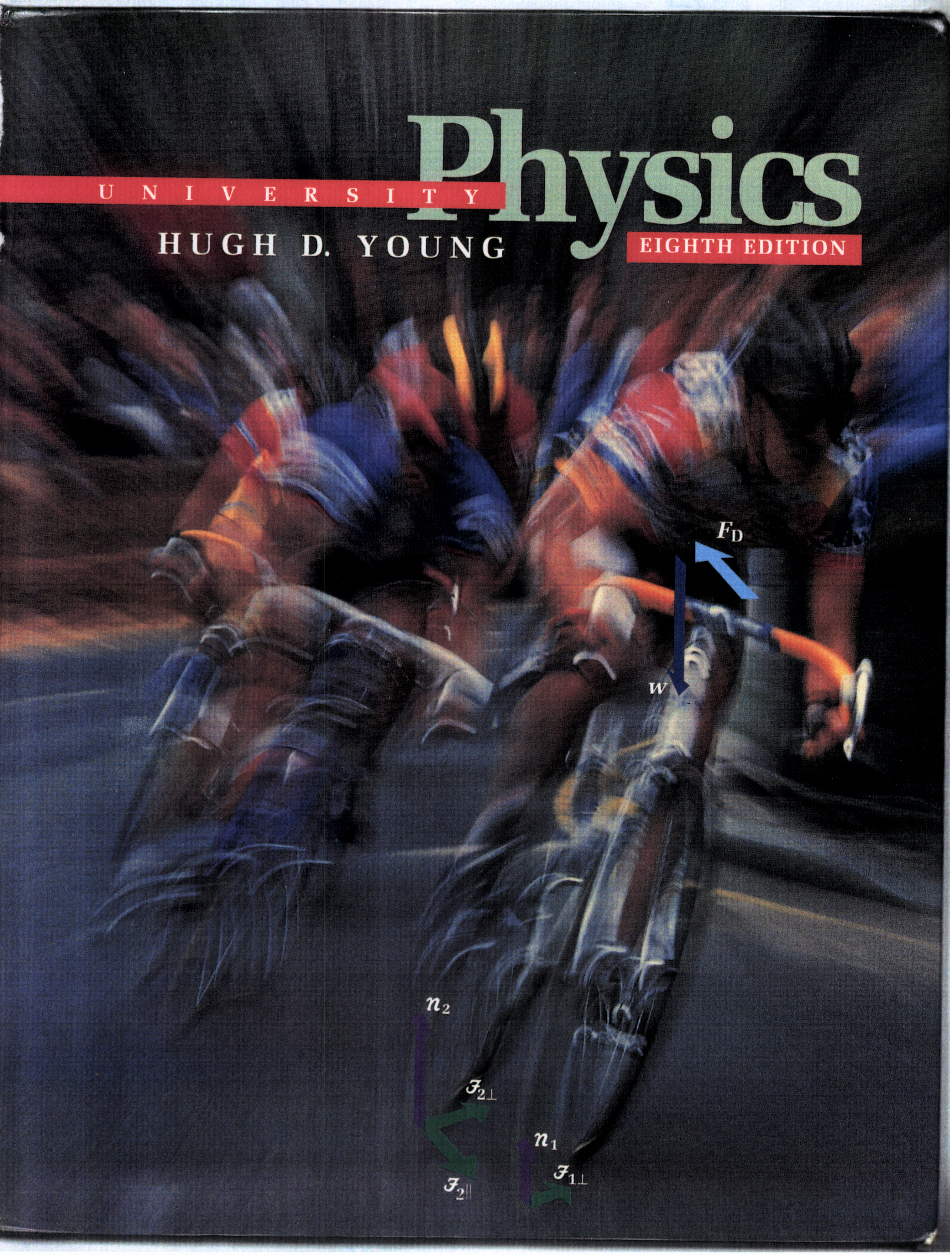

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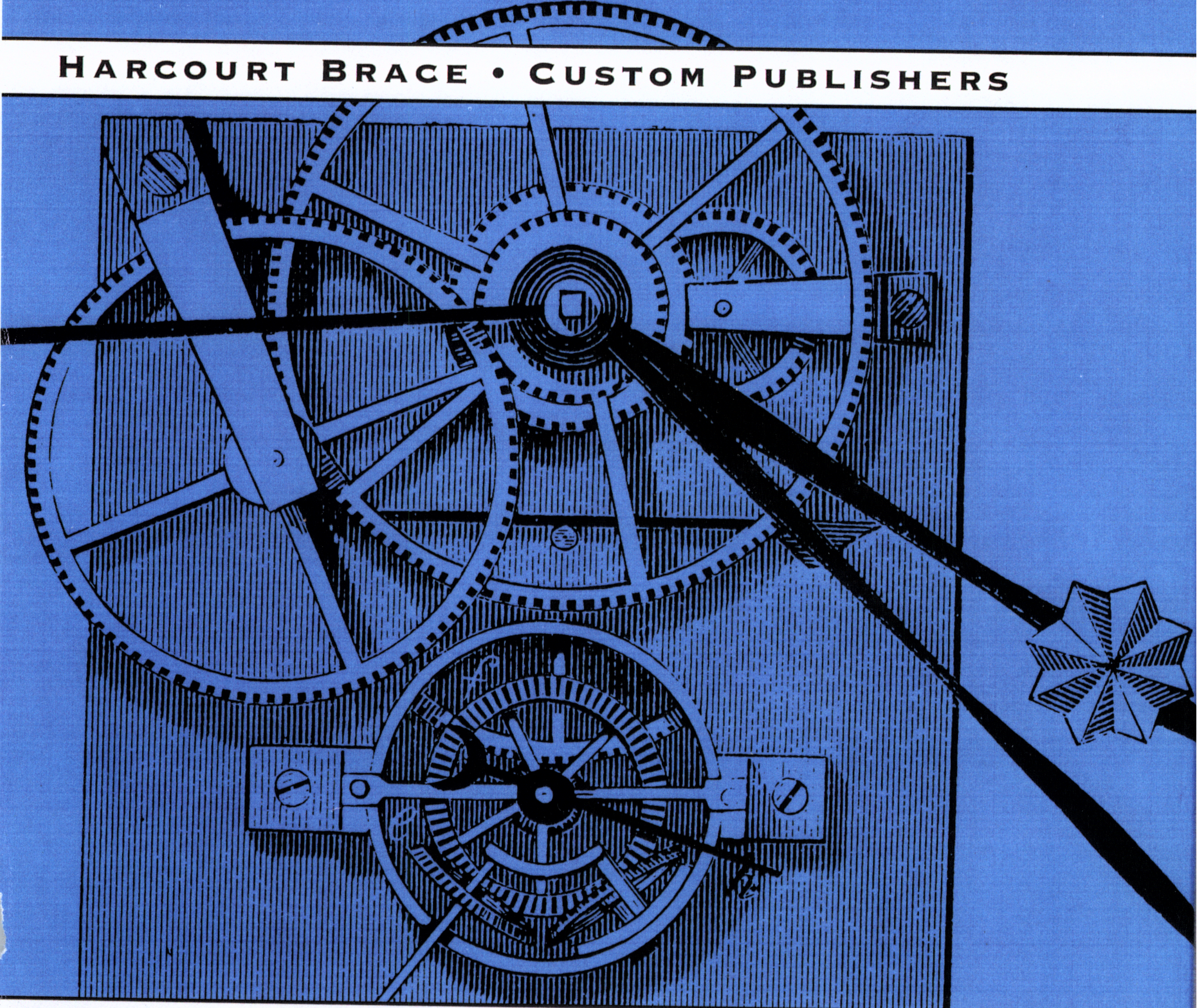

PRINCIPLES of PHYSICS

Serway

These textbook-cover images convincingly underscore the distinct realms of knowledge, students, and activity that attend each class. The picture of the racing bikes invites those who look at it, the physics majors, to "look at the world the way that physicists look at the world"--to take a real-world situation and then collapse it into a simple, streamlined mathematical model. Likewise, the machine on the cover of the engineering students' text delineates the boundaries that restrict the kind of relationship they can have with physics: they will use physics to build things. Similarly, the cover of the General Physics text sends a clear message to them regarding the role physics might play in their lives. Physics is all around them, in every sort of activity, and they might enrich their lives by gaining a glimpse of the insights physicists have into the world. An introductory section for Part One of the text, which deals with mechanics, frames this message even more tightly. Situated next to a large picture of two wind surfers, the first paragraph begins: "Physics is a science that deals with the fundamental principles that govern the behavior of the physical universe. It is a science that plays a role in nearly every aspect of our lives." (p.1) Once again, the text stresses to students that physics does have meaning for their lives, implying that these are students who do need to be convinced, even coaxed into this study. But analysis of this advertisement for physics coupled with comparison among the covers of the different books reveals a second, subtler but more powerful message: unlike the physics majors who will develop powerful conceptual tools for modeling the world, or the engineers who will borrow from those tools to design and build machines, the students of general physics are only briefly passing through the remarkable world of physics, with luck gaining some small appreciation of the complex and powerful formulations through which physicists understand the world. While real scientists will work directly "with the fundamental principles that govern the behavior of the physical universe," the rest of us must be content to passively experience the critical and ubiquitous role that physics will play in our lives.

The first line of the textbook's preface identifies the target audience: "This text is designed for a one-year course in college physics that uses algebra and trigonometry." (p. xix). Like Dr. Smith, the book indicates that what separates the students it serves from those who would use other texts and take other courses amounts to the level of mathematics the various students have studied. In our interview, Dr. Jones, the General physics professor, echoed this assertion, but with a twist:

Toby: So you've certainly taught majors, if not in the introductory class. OK great. Well, what I'd really like is if you could talk to me a little bit about how you perceive the similarities and differences in those different classes--are they different?

Dr. Jones: Well, in any class, there's always some people that aren't prepared mathematically. I don't care what level you're teaching at, there's always some that aren't prepared for that level, they just don't belong there somehow or other, but they got in there somehow or other. and there are students like that now in this class, that have trouble with algebra, you know. But I basically make it very clear in this class at the beginning: if you don't know this stuff, I'm not here to teach it to you, you're in the wrong class, and maybe you should get out, through the course, and some of them hang in there anyway. But even at the senior level, we have students that somehow or other manage to plod through and get to the senior level physics majors, still are not very good at doing the kind of mathematics you do at the senior level, which is vector calculus. So that's a common constant you see across all these courses I think, that there are always some people that aren't well-prepared for that particular level that they're taking. It does help that we have different levels, and that it'd be even worse if we didn't, there'd be a wider range of abilities in the courses.

T: So in other words, you perceive the differences among these courses, the way they're designed, as primarily mathematical, you know, what level, is this algebra, or calculus level, or...

Dr. J: You should look at our introductory courses, they're all teaching pretty much the same subject matter, it's just that they're going into it at different levels of detail, and different mathematical capabilities.

This professor spells out more clearly than the majors' professor the differences between students who are and aren't up to the mathematical speed of a given course. On Dr. Smith's account, the differentiation among the introductory sequences "basically comes about from our recognition that the students come in with a very wide range of preparations in terms of math." The various introductions to physics offered by the curriculum are intended to accommodate a student population with a diverse collection of educational backgrounds. Dr. Jones, however, expresses frustration that in every physics class, at any level, there are students who "just don't belong there somehow or other, but they got in there somehow or other." In these terms, rather than the courses following from the needs and abilities of the students, the courses set the standards, and the students either meet them, or they don't belong.

Dr. Jones described in the excerpt above the relatively ineffective process through which he polices the boundaries of his course: "I basically make it very clear in this class at the beginning: if you don't know this stuff, I'm not here to teach it to you, you're in the wrong class, and maybe you should get out, through the course, and some of them hang in there anyway." I was in the class to observe and record the real-time performance of this strategy, and it makes for provocative comparison. On the first day of class, Dr. Jones began by telling the students, "I cannot teach you physics, but I can certainly try to help you learn it." These sound more like words of encouragement than those of warning he described in the interview. In either case, what the comment stresses is that success in the class has emerge from the students themselves, not through the actions and words of the instructor. In the lecture, Dr. Jones continued: "If you haven't had physics [before this class], don't worry about it; if you know your math, you'll do fine. What is physics? It's a lot of math. Math is often a problem. Most physics classes require calculus, but that's not the case here."

The students are thus both reassured about their chances of performing successfully in the class, and reminded that they are different from normal physics students, who have the additional insights of calculus on their side. Of course, students' own experiences often subvert the rigid barriers among the classes. As Dr. Jones made this final comment about calculus, I watched a student in front of me lean over to a friend and ask, "Did you pass calculus?" The friend whispered back that indeed she had.

Dr. Jones continued his introduction to the course by identifying the range of students in attendance: "We have a wide variety of different majors in this class, all the way from English to Biology and Biochemistry. I've done some biophysics, so I have a little bit of empathy for those of you in Biology." As he spoke, two students near me carried on a dialogue on the pages of their notebooks, writing comments back and forth to one another. In response to these lines from the professor, one of the students wrote, "English Major?" with accenting underlines to express his shock. The other wrote back simply, "Yup." The students found it bizarre that an English major would take their physics course. They were likely from the other end of Dr. Jones's spectrum, Biology or Biochemistry; those departments accounted for a large percentage of the course's enrollment. Clearly, both the professor and the students had clear ideas about who fit into the class, and who was strangely and inappropriately out of place. Moreover, the professor's expression of empathy with students in biology suggests that he believes that a student's major has a particular impact on the way that student will understand and interact with physics.

Dr. Jones went on introducing his field: "Physics is a quantitative science; physicists like to say it's the study of everything." Like the textbook, the professor conveys to the students the universality of the knowledge they will encounter as the semester advances. But learning this universally applicable and powerful has its costs, and its difficulties, as Dr. Jones's next comment indicated: "Since it is a quantitative course, we have to talk about units." This sentence marked the rapid transition from the introductory portion of the lecture into the start of the real work of the course; the professor proceeded to begin familiarizing the students with the units they would need to keep track of as they worked on problems in physics. I have tried to indicate that this first-day introductory talk revealed a great deal about the assumptions that the curriculum and its implementers make about general physics students. But perhaps the most startling revelation of the brief event stems from its singularity: no such clear preliminaries heralded the commencement of either the majors' or the engineering students' courses. Those students, evidently, didn't need to be told why they should study physics or what they should expect from it. The majors were presumably studying physics because they wanted to, perhaps even because they felt called to; the engineers already knew that physics mattered to their lives because they would have need to mobilize it for their work in the future.

But I have argued to this point that these issues manifest themselves not only at the superficial levels of course overview and student stereotype, but also in the specific problem-solving activities of each course. And indeed, the general physics course followed suit in mapping out the possibilities and impossibilities for its students' relationships with physics through problem solving. In the previous sections, I stressed that physics majors' problem-solving activities focused on developing the conceptual strategies and physical intuition of a physicist, while engineers engaged in more goal-oriented problem-solving and emphasized real-world detail over conceptual depth. While the styles they are encouraged to develop are quite distinct, both sets of students are clearly on their way to becoming skilled problem-solvers. By contrast, General Physics presumes and expects little problem-solving skill and success from its students. In part, this inequity hinges on math; physics problems become more challenging as the math becomes more sophisticated, and as the professors all stressed, the general physics students are the least-skilled math solvers among the three classes. But the textbook and the class activities clearly point to other aspects of problem-solving for which the general physics students, unlike the majors and the engineers, will surely need remediation. This passage from the preface to the text illuminates these differences:

> "Many students tend to focus largely on finding the right equation to solve a problem. They do not see that equations are consequences of *concepts*, concepts that express physical ideas. We believe that good problem-solving techniques start with a foundation of conceptual understanding. Therefore, have added to the text 108 examples [since the previous edition]...that are entirely conceptual in nature. The intent is to provide students with explicit models of how to 'think through' a problem before attempting to solve it numerically." (p. xix)

Students are thus to be taught how to perform physics--how to go through the motions. And for this they need models, because they lack the innate problem-solving instincts of the 'natural' physicist. While Dr. Smith, the physics majors' professor, was content merely to model his own problem-solving style to the class and have the students pick up often-tacit cues, the General Physics curriculum assumes its students need to be lead step-by-step through the process of solving a problem. The text thus includes 'solved problems' at the end of each chapter--detailed solutions to difficult problems that students are to study and attempt to mimic in their own solutions. Noting that "Careful reasoning is the cornerstone of problem solving," the text also includes sections on reasoning and "reasoning strategies" which "explain what motivates our procedure for solving the problem before any numerical solution is carried out." (p.xx) Further still, the margins alongside the examples in the chapters are peppered with sidebar "problem solving insights," described in the user's guide as "Brief comments in the margin [which] reinforce important aspects of problem solving that might otherwise go unnoticed." (p.xxvii)

The general physics text and professor see their students as lacking some sort of innate problem-solving talents that the majors and engineers bring to their classes. This lack of problem-solving insight leaves the students haphazardly hunting for the proper equation with which to solve a problem rather than reasoning their way to the solution. In the following class excerpt, Dr. Jones introduces the students to the equations of kinematics, and then leads them through the process of selecting among those equations and solving a problem:

Dr. Jones: "These are our four equations for constant acceleration. These two equations, remember, have nothing to do with them, that's not already contained in those two basic equations. So they're a little more complicated, and if you have trouble remembering them, you can always get them from the two. You can always solve every problem using those two. Two very simple equations. However, these can save you some time, if you can remember them. And your book gives you a very nice little table of all 4 of these...I had someone come up after class last time, and say, 'I remember these equations from high school,. but no one ever told us how they got 'em.' he thanked me for showing him how to get the equations. Of course, it's in your book, too. OK, let's look at the full set of these equations, and study a little bit about the variables involved. The point of this will be how to make your decision about how to choose which one of these to use.

This is a table that's in your book. Since I've indicated....as we said, you've got 5 variables, so you need to know 3 of them to calculate the other 2. And so you look, for example if your were working a problem, and the problem said nothing about the position, all the problem dealt with was acceleration, velocity, and time, then this first equation is a very good equation to use. (It's a) very simple equation, it has no position in it, and if you're not interested in position, it's probably the equation you want to use. All the other 3 have the position in them--x, x, x, in fact you see there are marks for x-that means the variable's included in the equation. If you wanted to work a problem that didn't care at all about acceleration, all it's concerned with are position, velocity, and time, then this would be the equation to use, because it doesn't involve acceleration, and it does involve the other 4. And then a problem that didn't care at all about the final velocity, then this would be the correct equation to use for that, because it's the only one that doesn't involve the final velocity. Similarly, if you had a problem that didn't care at all about the time, and this occurs quite often, that you don't care at all about the time, often you just want to know velocities and positions, together with accelerations, that's all you'd want to use. Notice these 2 equations are quadratic, and that can cause, not problems, but something you have to watch out for, because whenever you solve a quadratic equation, how many solutions do you get? [student answers, Dr. Jones repeats] 2. You get 2 solutions. One of the solutions may not be a correct solution, depending on how the problem is stated. Both may be correct solutions. A problem may say they're only interested in one of those solutions, and that's the solution that you want to report, not both of them. And you want to give a reasoning why you chose the one you chose. We'll work a couple of problems like that. Remember, this is only for constant acceleration. Do not ever use these equations except for constant acceleration. If the acceleration is not constant, you have to go back to the first equations I wrote on the board today--definitions, of average velocity, accelerations, etc. You can also always do things graphically, that's the last thing we'll do today....Any questions about this? You're going to work a lot of problems using these kinematics equations. Let's talk a little bit about working problems--what kind of techniques you want to use, procedures to follow...

This exhaustive detail amounts to a sort of "hand-holding" approach to teaching problem-solving. In particular, the students are given extremely explicit instructions about how to select among equations, and what to do once they make a selection. These classroom scenes demonstrate repeatedly the emphasis the instructor placed on giving students specific instructions about the way they should go about choosing the proper equation with which to solve the problem. Remarkably, comparison between this equation-seeking approach and the emphasis in the majors' class on developing and relying on physical intuition to conceptually frame a problem precisely parallels the distinction we reviewed in the problem-solving literature between novice and expert problem-solvers. On that account, experts approach a problem by beginning with a line of qualitative analysis which quickly leads them to the appropriate equation, while the novice "tries to do a quantitative analysis first, by thinking through all the equations that could conceivably apply," and further, "to sort through this welter of formulae, the novice draws on ill-developed qualitative ideas..."

Clearly, this expert-novice research on problem-solving favors the expert model, and advocates strategies for teaching novices to think more like experts--the same goal the Dr. Smith described to me. Further, the passage I quoted above from the general physics text describes the same effort to emphasize conceptual and qualitative analysis over equation-hunting. But I insist that the three-class introductory physics curriculum I studied doesn't train all of its students to be expert problem solvers, because it doesn't conceive of all of them as potential physics experts. Another day in class, Dr. Jones referred back to the equation table he described in the passage I cited above:

Dr. Jones: Remember that we had this little table. You don't need this little table, all you need to do is just look at the equations and see what the variables are...you don't need to memorize this table or carry it around with you. You need to know the equations, that's what you need to know. As you're working out these problems, you'll dream about them at night.

Once again, there is no reference to qualitative analysis or physical intuition, to conceptualizing the physical scenario; students are simply supposed to familiarize themselves with the set of equations they need to do their homework, and to hone their skills at selecting among and solving for those equations. I want to stress that this doesn't necessarily mean the professor sets a low standard of performance for the students; after all, he expects them to know their equations so well they dream about them at night. The point is that they are to excel at a different kind of problem-solving approach than the majors.

I want to turn to one final comparison to elicit these problem-solving and physics-performing differences more convincingly. On different occasions in both the majors' class and the general class, a student asked whether they would be able to use crib sheets on quizzes and tests. The responses are revealing:

From General Physics:
Student: "On the quizzes are we going to have equation sheets?

Professor Jones: "Not on the quizzes. Possibly on the final exam, we'll see about that, but not on the quizzes. The quizzes are over the previous week's work, you should remember the previous week's work, if you've done all the homework. You can use a calculator, but not one that stores equations."

Student: "What if that's the only calculator you have?"

Professor Jones: "Well, just don't store any equations in it." (class laughs)

From Foundations of Physics:
Student: "On the tests, are we going have to memorize the equations, or..."

Professor Smith: "Memorizing equations for tests that's a very good question. I'll give you a crib sheet, OK? So you will get a formula sheet for the test. Not that I think the formula sheets help you very much. I don't think that they help you very much. But that's at least one little headache that you don't have to worry about. It's like a security blanket...I'll just copy portions out of the book, and it's up to you to know which one is useful, and which ones are just specialized...anyway, I'll give you the formulas, so don't worry to much about that. Try to think more about the physics involved. That's what you're trying to remember it for. Not mathematics. Mathematics we learn in calculus course. Here you're trying to learn physics, and maybe apply a little bit of mathematics."

While the General class emphasizes memorizing equations above all else, the majors are told not to worry so much about equations and math. Instead, they should "Try to think more about the physics involved," because after all, they're the ones who are going to be physicists, who are destined to probe the fundamental secrets of the universe. While their performances on exams are important, they are secondary to the real goal of producing students who will one day do good physics, who will look at the world the way a physicist does. The general students, on the other hand, need to focus on learning the material and practicing the strategies that will help them to perform well on tests, get good grades, and successfully complete the physics requirement for their own alternate major tracks.

Chapter 3
Solving for the Unknowns: The Dynamics of Student Agency

In the last chapter I devoted my energy and attention to mapping out the differences among three distinct and coherent introductory physics settings and communities. In emphasizing difference among the classes, I often ignored or eclipsed differences and tensions within them. In this chapter, I set out to remedy that deficiency. I didn't stress uniformity within the classes accidentally; rather, I conclude that the classes rely on stereotypes and on disciplinary boundaries for coherence, for the kinds of structures of meaning through which we make sense of and lend order to a hopelessly complex world. Shifting my attention from the curriculum and its implementers to students, I will explore the ways various students negotiate with and navigate within these structures, the ways they make sense of themselves and of physics by alternatively embracing or resisting, reinscribing or undermining these rigid disciplinary divisions.

I originally conceived of this chapter in four sections--one devoted to each of the three sets of students I drew for interviews from the three classes, respectively, and a fourth for those students among the three sets who, because they didn't fit well into any of the prescribed categories of the curriculum, I called 'boundary creatures.'[4] My boundary creatures included an engineering major who chose to take the physics majors' class instead of the engineers', a physics major who had dropped her majors' class and was, at the time of our interview, uncertain as to whether or not she could return to the course the next semester and go on as a physics major, and a former major who dropped the majors' class in exchange for General physics. As I interviewed students and analyzed data, I increasingly realized that, in a way, all of the students I interviewed, and all of the students in the classes, were boundary creatures: none of them do or possibly could fit their curricularly-assigned mold exactly, and all of them constantly move back and forth across

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[4]Donna Haraway uses the term "boundary creatures" to describe simians, cyborgs, and women, highlighting the marginality and ambiguities of each category. (1991, p.2) Likewise, I want to focus on the marginal positions and ambiguous identities occupied by students.

the artificial-but-powerful curricular and cultural boundaries that organize and restrict their learning activities.

To make sense of these boundaries between classes, I borrow from Donna Haraway's description of "bodies as objects of social knowledge." She writes that

> [t]heir *boundaries* materialize in social interaction. Boundaries are drawn by mapping practices; 'objects' do not pre-exist as such. Objects are boundary projects. But boundaries shift from within; boundaries are very tricky. What boundaries provisionally contain remains generative, productive of meanings and bodies. Siting (sighting) boundaries is a risky practice. (1991: 200-201)

Curriculum development, and likewise ethnographic research and writing, are kinds of 'mapping practices,' so in this project I am both tracing and producing the boundaries that partition these students' experiences. And these boundaries have consequences for both the meanings of physics and the bodies and identities of students. So as I craft this chapter, I will retain the framework of my boundaries, but I will also try to remain critically and reflexively conscious of the risks of sighting (in my role as 'participant-observer') and siting (in my role as author) those boundaries where I have. In order to tell the rest of this story about three classes, I use a section for each class, allowing the structure that governs the student's experiences to similarly govern my writing. But the boundaries between those sections will be permeable; within each, through the voices and agency of the students grappling with the structure of the courses, I will try to let emerge three stories that have at once oppressively clear and liberatingly blurry demarcations, and at once profoundly distinct and deeply contested meanings.

Physics Majors

None of the uniform course pictures I mapped out in the last chapter is more problematic than that for physics majors, for in fact, actual majors make up a minority of the enrollment for the class. The class also includes large blocks of students from chemistry, who still fit Dr. Smith's description of future physical science researchers, and who presumably, as future chemists, share enough of the young physicist's conceptual framework and physical intuition to be able to fit into the class, and from mathematics, who will of course bring with them sophisticated enough grasps of math that the kind of mathematical modeling of the world that Dr. Smith stresses will be accessible to them. Not all the outsiders in the class were so easily assimilated, as this conversation reveals:

Toby: When you say that, well, [Foundations of Physics], I mean, I guess actually most of the students in that class aren't physics majors...

Dr. Smith: I'd say about a third of them are physics majors, then there are chemistry or biology majors who take that, and then there are some students from completely other, different fields, like building construction. There's a big class of students from building construction.

T: Oh, I missed that. How did that happen?

Dr. S: I believe, this is just a guess, but I believe that they signed up for this course because it didn't have as many prerequisites as the engineering one, and it still satisfies their curriculum requirements. It's odd, but that's the way...

T: That's very strange.

Dr. S: Well the engineering school is very specific about the things that they want students to take. They want that course tailored exactly to their specifications. And so although this course that I'm teaching has a tougher math requirement, just in terms of preparation, it turns out to have less in terms of formal prerequisites. So...It's odd how these things work out.

T: Yeah, that's very strange. Do you think that they were sorry about their choice?

Dr. S: I...don't know. They generally didn't do as well as the chemistry and physics majors, but they didn't...fail the course or anything...

I was startled by this passage when I first read through the interview transcript, because my own responses reveal as many of the class's assumptions as do the professor's comments. The diversity of student majors in that class wasn't news to me; I knew there were math and chemistry majors, and even the odd engineering major[5], but on learning of these students from building construction I was clearly surprised. Dr. Smith and I shared

[5]I never managed to find any of the biology students the professor spoke of, but there were evidently a few. They are actually required to take Elements of Physics, the calculus-based counterpart to general physics which was not offered during my fieldwork semester, so some who could not wait another semester to meet the requirement were likely forced to choose between one of the other calculus-based sequences, Principles and Fundamentals, and opted for Fundamentals on the same grounds of requirements as the building construction students the professor spoke of.

firm assumptions about who belonged in this sort of course, so that physics majors were obviously the ideal fit, and students in chemistry and math came acceptably close to fitting. But something like building construction carried with it for both of us all of the worst connotations of "practical application" and "trade training" that, to a lesser degree, attended the idea of an engineering student visiting the physics department for a few courses. Our repeated expressions of how "odd" and "strange" we found this phenomenon reveal the ways that our assumptions about different kinds of students police the boundaries of classes and disciplines, clearly spelling out who does and doesn't belong. Also, Dr. Smith describes the students' presence in the class as if it were the result of their confused wanderings though the course catalog. As it turns out, however, the Building Construction department requires its students to take Foundations of Physics, though it does allow them the option of substituting the odd combination of the Principles of Physics lecture and the General Physics lab. This ironic twist reflects the critical issue of this chapter: that distinctions between accounts in which curricular structures govern student's activities and identities, and those which posit students as agents actively generating their own senses of academic selfhood and relationships with knowledge, dissolve in the real-time interplay of pedagogy and learners into complex phenomena which resist description in the too-simple terms of "structure" and "agency."

So I'll turn now to the words of the classroom agents in hopes of understanding how they understand themselves as physics students, and particularly, as physics problem-solvers. This first student's response to my questions about how he found his problem sets and exams echoes Professor Smith's emphasis on the conceptual dimensions of a problem:

Matthew: They're...well, they don't seem to be too bad...of course, some of them always stump you when you look at them the first time. But they don't seem to be too bad. Actually, some of them...there's one, some of the chapters were rather disappointing, because they're so incredibly...it's just plugging in numbers. It's not anything like...prove a formula, or, I mean, of course we don't have enough math to do that, but, it's still, it's kind of disappointing, cause there just...there's no creativity in the problem. It's just plugging in numbers, and put down an answer. Like the chapter on gravity was notorious...I did every problem in the whole chapter, and every problem was just plugging in numbers, except for one, but that was pretty close to being plugging in numbers.

Toby: So you were disappointed because it wasn't challenging enough?

M: Um-hm. It was...it wasn't very interesting.

T: How about the tests?

M: The test, well the test was kind of difficult. But that was...it was multiple choice, so you didn't have much leeway.

T: (laughs) Got it. You can't be creative with that, I suppose.

M: Right.

Matthew was actually disappointed when he had to solve problems that didn't challenge him conceptually, that didn't help develop his physical intuition and allow him to be creative. He did, nonetheless, solve every problem in the chapter--far more problems than he was assigned. I asked him why he spent so much more time than was required of him:

Matthew: Well, I kind of like gravity, so...well, I like physics in general, but I have a friend that...we...he's...we work...we go and spend time doing all the problems. So that way we figure the more problems we do, the better we'll be at it. So we just do all the problems, or we try to. We skip the ones that are obvious, but we usually do all of them.

Toby: So, are you doing that...is that for your grade, or is that for...

M: Do we get extra credit for it?

T: Yeah, or...are you trying to make sure that you'll do better on the tests, or is it...does it go beyond just what you're doing in the class, just for your grade, to do the extra work?

M: I don't think it's just for the grade, cause, if it was just for the grade, I wouldn't have to be a physics major. But, so I don't think that...I guess it's to make sure I don't flub up, and at the same time, so I can learn how to interpret lots of different physical situations.

T: So...I mean, is that fun?

M: Yeah, it is.

Matthew, then, behaves as the ideal physics major, as everything the curriculum expects him to be: he solves problems to develop his physical intuition and his conceptual handle on the material, and because they're fun. More critically, such behavior follows from his sense of disciplinary selfhood: if he didn't want to work problems that way, he "wouldn't have to be a physics major."

Another student I interviewed had recently dropped the Foundations of Physics course, and was uncertain whether she would take it again with more success the next semester, or be forced to find another major. I asked her why she dropped, and she replied:

Janet: Yes. I dropped...I placed out of [first-semester calculus] because of the AP exam I took in high school, so I'm in [second-semester calculus], and the physics professor when he went over my schedule with me at summer orientation, placed me in [Foundations of Physics, which without the AP credit, she wouldn't have taken until her sophomore year] because of that, because you need a background in calculus for [Foundations of Physics] I think, and I had it. The thing is, I don't have the background in vectors I needed. I'm doing that now. I just got...right after I dropped the class, I got some of the vectors in vector geometry, and I needed that at the beginning instead of now. So that should help when I retake the class.

Toby: Fair enough. Tell me a little about what kinds of problems that posed for you when you...tell me about sitting in class and not knowing about vectors.

J: And not knowing about vectors...Um, well the problem didn't come...I mean when you do like vector diagrams, where you do diagrams of the forces, I could do that fine, I could understand that, but when it came like to the algebra that had to do with vectors, was where I had problems. He would go on describe something, and I had no...I had trouble following how he derived it. And some of those derivations you had to use to figure out stuff in later problems on the homework. So I couldn't do it. I got stuck like halfway through. Those were the types of problems I had. It was not concepts, it was algebra-type things.

This distinction between concepts and algebra is essential. Despite her setback, and the insecurity it generated, Janet still considers herself a physics major, and still hopes to get back on track. So she is quick to stress that although she had a few key holes in her math background, those have since been remedied, and more importantly, her ability to think like a physicist was never in doubt. She didn't have any trouble conceptualizing problems, drawing vectors diagrams, and so forth, she just "got stuck...halfway through," when she got to working out the mathematical details. Like her professor, who admitted the difficulty with "keeping track of nitty gritties" which distinguished him from an engineer, she might have stumbled on some mathematical detail, but such troubles are secondary for real physicists. When she told me that if, when she tried physics again the next semester, she still struggled, she'd probably have to give up on physics and change majors, I pushed the math issue further:

Toby: So if you do that, will it be to get away from the nasty math? I mean is that the...

Janet: Not really. Because some of the math is just as nasty, like, in calculus. The amount of algebraic nit picky little things you have to do, like with integrals, some of them are...are horrible.

T: Yeah, that's true.

J: But it's not to get...really to get away from the nasty math, because you can almost always work through it, if you know the concepts, and you have enough notes on it. It'll be more to get away from, actually, probably the method of thinking, just thinking...I don't know...if I can't learn...there has to be a trick I believe, I don't know if this is right or not, there has to be a trick, a method of making yourself recognize certain situations, in physics, so that when you come across a problem, you know where to look for solutions, and if I can't figure out how to do that, I'm going to have a real problem, (chuckles) so...I figure that that'll be, I don't know. It'll be because of that, not because of the math...the more you do it, I mean the more advanced you get, the easier it is to recognize situations, and to figure out what to do with them. I mean, the longer I do integrals, the easier they get. Algebra is pretty easy now, it wasn't back then (laughs) but it is now. So, yeah. I figure the longer I can do it, the more practice I get at it, the easier it is to bring to math situations to like, to be able to create new ones, or be able to like, to pull two of them together is really, I think, the goal of it, so that you can, like, take a problem that has two concepts, and pull them together in a different...to solve in a different way. That's what, like, the aim, I think, of this kind of course, and I need to be able to do that.

Janet stresses that what will determine her success or failure as a physics major will be whether or not she can figure out the "method of making yourself recognize certain situations in physics," the kind of skills in conceptualization and qualitative analysis that a good physicist utilizes. She believes that in her next round with physics she'll find out whether or not she has what it takes, whether or not she can learn to think like a physicist. If she does, she'll continue on as a physics major; if she doesn't, she's "going to have a real problem," and she'll have to find a different major. She captures, in a nutshell, the interrelations between problem-solving and disciplinary identity: to succeed as a physics major, she will have to perform a particular kind of approach to physics, with emphases on physical intuition and conceptualization, rather than mathematical fine points or real-world details--emphases that reflect the priorities of professional physicists.

Of course, few if any of these physics majors are likely to end up as professional physicists; the road is long and difficult, and the jobs at the end are increasingly few in number. I spoke with Professor Smith about this grim reality:

T: Anyway, at least the students who are taking this class who are majors, it seems to me that, I mean, one of the things that I've been trying to track is essentially motivation--what are these kids taking physics for? The kids who are majors, presumably, are intending to take lots of physics, I mean I think all of them are imagining that they're going to become physicists. I mean, I was a physics major who imagined that once.

S: So was my brother-in-law, and he ended up on Wall Street making more than a million dollars a year. He learned his lesson. Some of us never do.

Professor Smith skirts my question, but his response couldn't be more revealing. "Some of us," those who really do make it in physics, never do learn their lesson--that they could surely be pursuing more lucrative occupations--because doing physics certainly isn't about money or a job. Physicists do physics for the sheer and simple love of it. One of the students summarizes:

Toby: Right, so do you see any chance that you'll wind up...I mean, what are you going to do if you don't do physics? I mean, I know you might be a math major...

Matthew: I'll work in patent office. (we laugh)

A patent office--Einstein's earliest occupation, where he worked while he wrote his first famous papers on relativity. In other words, unlike, say, engineering, physics isn't a vocation, but an avocation. If Matthew can't manage to find a job as a professional physicist, he'll find something else to subsist on, and continue to explore the mysteries of physics on the side. He told me that if he couldn't find a teaching or research job with his physics degrees, he'd settle for being "kind of [an] industrial physicist...there's always spare time on the side to do other things"--other things like real physics.

But not all the physics majors were satisfied customers. One of the General Physics students I interviewed told me about her lab partner, who had begun as a physics major, but switched paths:

Molly: I have a friend that was majoring in physics, and he had to drop it. He was just ...he's just so angry at the physics department here, he's just like...

Toby: Wow. He wasn't in your class then, he was in [Foundations of Physics]?

M: He took the engineering physics part. Or some kind of physics major [class]. He said that that was his original major, he said he had (professor). (Professor) turned him off so bad from physics, I mean, he didn't even go over vectors. He skipped over vectors completely, and this guy's going, you know, wait a minute, this is a second level course, you know, I understand that most of the people who are going to be in that maybe would have taken physics in high school, but you generally don't necessarily always know what you want to do in high school, and aren't going to take physics unless you are forced to or something (laughs). But [the student's first physics professor] totally skipped over vectors and everything, and this guy got so angry he just quit physics altogether I guess. He's taking physics now I guess with (another General Physics professor), and he said that he considered (that other professor) the best teacher in the department. He said "he's a really good teacher, da da da da da", and he allowed them to have problem set or a sheet of problem...equation sheet or whatever, Jones wouldn't let us.

Like Janet, Molly's friend couldn't keep up in Foundations of Physics because he lacked sufficient background in vector math. But unlike Janet, Molly's friend got angry at the professor, the department, and the curriculum. Frustrated that the major's course left him behind, he changed majors, but still took a physics class, one where he would be taught the math he needed to know to study physics. For him, then, learning physics came at the expense of becoming a physicist.

Engineering Majors

All three of the physics classes I attended took place in the same room, a large lecture hall with seats for nearly 200 students. The wooden row seats sat on metal frames, and each featured a small fold-up wooden desk that squeaked its way up upon demand from beside the next seat. The chair-desks had clearly seen years of service, and inked, scribbled, or etched into nearly every wooden seat-back or desktop were volumes of student graffiti, the silent musings and amusings of countless classes of bored or frustrated physics vandals. Fascinated by these running commentaries from semesters past, I made sure to examine the nearby scrawlings every time I tried a new seat. Some of my favorites were these, which I recorded in my field notes the first day of the engineering physics class: "Written on my desk, mostly erased and barely legible, but looks like: 'Damn it Jim, I'm an engineer not a physicist!' And on a neighboring desk, more simply, 'Physics = Death.'"

The first author's Star Trek-style declaration compellingly demonstrates the intertwining of knowledge and selfhood in introductory physics. For this student, identification with a major other than physics provides sufficient grounds for struggles and frustration for physics. Just as Bones's reminders to Captain Kirk that he's a doctor and not some other sort of Star Fleet professional excuse him from the standards of performance for that profession, this student sees recourse to his engineering identity logically excluding the possibility that he should be expected to do physics.

In the last chapter I devoted considerable attention to demonstrating through classroom transcript excerpts the different ways professors modeled problem-solving in the majors' and General Physics courses, but offered no such extended example from the engineering course. I chose to organize the data that way because the problem-solving moments in the engineering class were unremarkable; if anything, what distinguished the events themselves from the other classes, in particular the also-calculus-based majors' course, was the lack of telling references to who the students were and how they would use this knowledge. Instead, this information emerged from both the professors' and the students' comments to me outside the class about the professor's in-lecture demonstrations of problem-solving. The engineering physics professor told me in our interview about his frustration at the decline of student interest in his classes in recent years:

Dr. Davis: Well, that's one of the big problems. Getting any kind of response out of them is just really difficult. And it's gotten much much worse in recent years. I retire this summer, and I tell you, I'm more than ready to step out of this thing. I just, I tell you, I used to really look forward to the Fall term, and being teaching these courses, because there were always, in these large engineering sequences at least, there were always a percentage of students who were the better students in the university, I think the engineering students generally are better students, and there were always 10 or 15 percent perhaps, that would get turned on by the course, and would converse, you know, would be interested. And now I don't see that, hardly. I mean, mostly they just kind of sat there with...Maybe it's me, I don't know, maybe I'm just getting old and tired, but I just can't...and I encourage them. I said look, I get yelled at over the hold all the time. What really throws me is when they sat there in stunned silence, when I say something, you know, and I know it's going over the head of perhaps a large number of them. And somebody will sit there, and instead of throwing something at me, or raising their hand, or voicing an, you know, please explain that, they'll just sit there, in silence. And it's hard to read minds. You can't read minds. So I would...I get very unhappy, and dissatisfied with the level of student...intervention, I'll call it, because I know that they have lots of questions that never get asked. Some guys sit there, and I guess they're afraid of looking dumb or something. And yet you know, if you're a student like that in a class of that size, and something isn't ringing in your head, then it's not ringing in many heads. So you're doing a big favor to the class to say "stop" and ask questions. But I don't get much of that interaction. And it's gotten to be very discouraging.

Similarly, Dr. Smith compared the students in his current class to those he had taught in the engineering sequence in previous semesters:

Toby: Then again, orienting more toward the current students, having taught [Principles of Physics], do you notice differences in the ways that students approach the course, experience the course, operate in the course...

Dr. Smith: Yes, yes. I think it comes back to this question of motivation. Students in general, when I was teaching [Principles of Physics], were interested in how, specifically they were interested in what grade they were going to get, and virtually any question that they asked was oriented towards improving that bottom line. They were very task-oriented students, whereas the students that I see now tend to ask questions just for curiosity, it seems. I tend to see less emphasis on what...on having questions posed and then answered in order to improve a grade. The connection may still be there in the end, but it's a lot more circuitous...a lot more circuitous.

Both professors bemoan the apparent lack of real interest in physics for physics' sake on the part of their students from engineering. But on the curricular model I developed in the last chapter, unresponsiveness, apparent disinterest, task-orientation, and grade grubbing are the only behaviors and attitudes they can reasonably expect from the engineering students. By dividing the introductory physics courses along disciplinary lines, the curriculum emphasizes the distinctive disciplinary identities that attend those different majors. And engineers, as we saw in the last chapter, aren't studying physics for love of knowledge, they're studying it to build better bridges. A curriculum that presumes engineering students who have a purely practical relationship with physics presumes "task-oriented" students who care little about the deeper beauties and wonders of physics. After all, damn it, they're engineers, not physicists.

But of course, this picture is too simple. A lecture-sized class of 150 students, engineering majors or otherwise, forms a diverse, heterogeneous, and complex population. And the professors' accounts of the engineering students' behaviors and attitudes will surely not always match the stories those engineering students tell about themselves. In one of my interviews, I spoke with a student in Foundations of Physics who turned out to be an engineering major. His comments provide a helpful bridge between the last section and this one:

Toby: OK, so...this thing about...you're an engineer. What are you doing in a course for physics majors?

Amos: Well, I knew I was going to apply to med school, and they require physics with lab, so I decided rather than taking the general physics with lab, I'd like to take a calculus-based physics with lab. So I got special permission to take Foundations of Physics with the lab instead of Principles. The only disadvantage is that it covers...basically everything we've done so far, we've already done in statics and dynamics, the engineering courses. So it's repetitive, or simplistic in most cases, except for the angular momentum stuff, we haven't done much with the rotational bodies, but all the linear momentum we did in physics, the torque and what-not.

One of the fascinating pieces of this story is that rather than simply submitting to the structure imposed on him by the course catalog, Amos chooses to use the curriculum to his advantage, breaking out of the mold of his major to take the physics majors' course because he hopes it will help him get into medical school. Of course, this strategy also reflects his career plans; though he majors in engineering, he doesn't anticipate an engineering career, so his stakes in that disciplinary identity are perhaps different from those of other engineering students. Moreover, as Amos notes, there is a disadvantage. We continued:

T: OK, so when you see it in this course, you're not...there's no new twist on it, there's nothing different about it, it hasn't gotten any more interesting?

A: Well...

T: I mean, presumably you weren't seeing it with calculus before, right?

A: No, not much calculus, maybe a little bit of calculus, but here the calculus only comes in in the derivations of the formulas, and the homework assignments are easier than they were in engineering. In engineering the big emphasis is on problem-solving, whereas I guess it's more in the derivations and theories in physics. So the problems have not been very tough at all.

T: What about the derivations? I mean, do you...

A: There are some things that are really tough to follow, but it's certainly explained in more detail. I mean, in engineering we sort of brush over the derivations in a lot of cases, and the emphasis is over problem-solving. But I mean I tend to...I try to go over the derivations for the physics stuff. I mean, maybe it's just 'cause I'm an engineer, but I mean it's not that important to me, and I'd rather just sort of get the problems done, and get a basic idea of what the...I mean, I'd like to know how to work the logic backwards from the physics problems that I'm doing. But it's not usually worth the time, it's not much to do much more than just what it takes to solve the problems in physics.

T: So while being in this course had its advantages in terms of your transcript and things like that, you'd probably really feel more at home in an engineering, Principles of Physics class?

A: (nods) And the physics lab for this, I mean it's getting better I guess, but the first 2 or 3 labs at the very least were just ridiculously simple.

Amos's distinction between engineering's problem-solving emphasis and the focus on theory and derivation in physics parallels my distinction between problem-solving approaches in the two classes. What Amos calls problem-solving is what happens after the conceptual work, if any, is finished--it's about plugging in the numbers, doing the math, and getting a solution. The other stuff--the conceptual framing, and the emphasis on thinking about the physical situation like a physicist would, that comprise the essence of problem-solving in the physics majors' model--aren't "worth the time," are too "much more than just what it takes to solve the problems in physics." Even more provocatively, Amos attributes this attitude to his disciplinary identity: "maybe it's just 'cause I'm an engineer." Later in the interview, he came to speak of the work that the professor did in class as problem-solving, but of an inefficient sort:

Toby: Do you think that the class is...I mean, maybe the class isn't quite right for you because of your particular background. Do you think it's a bad class?

Amos: (pauses) I wouldn't say it's a bad class, but I certainly am not satisfied. I just don't think that...it seems like, I mean, today, especially. He went over two problems in class, the whole class. That just seemed like he was taking it very very slowly, almost too slowly. That might be my complaint.

T: So it's not that you want him to be doing something other than problems, but you want him to move through problems a little more quickly?

A: Yeah, that's almost what I'm wishing for.

The Principles of Physics students I spoke to echoed Amos's distinctions. One of them, Karl, mapped these different problem-solving frameworks onto differences between homework problems, which came from the textbook, and exam problems, which were drawn from the professor's "database" of problems that he had compiled over his three decades of physics teaching and printed as a supplemental packet of course materials the students had to buy for the course:

Karl: ...the database questions for me were difficult, because it...I don't know, I tend to have a tendency to analyze stuff too much, but they just seemed to be so much different then what was given in the book.

T: Oh yeah? How?

K: I guess some of the problems that we find in the book are more number-crunching type problems, whereas his problems on the test, they may use the same basic principles, but it seems that you have to have a more...just a greater understanding of the material itself to be able to come up with generalizations on how something may end up coming about in the problem. Like it may not necessarily be a number, one of the things he would talk about is, given a certain amount of information in the problem, can you determine whether the fields or whatever, vector fields, what they B, or you know, would be going into the board, out of the board, up, down, you know, which direction is it in? Sometimes those more or less generalizations, not necessarily exact numbers, coming out.

T: So that stuff is harder to work with?

K: For me it is.

T: How come? Why did you say "*for me* it is?"

K: I don't know...I don't seem to deal well with things that are abstract, I seem to deal well with things that come out when there's one solution, one answer, you know, you can see where it's coming from, where some of the stuff you can't really see where it's coming from, and even if you study the material in the book, sometimes it's hard to grasp the concept, sometimes it's not presented very well. And trying to go by what the instructor is saying, and then going by what the book is saying, and then trying to put it together, it doesn't seem to work, and I've had a hard time dealing with that.

While Amos simply found these qualitatively-oriented problems boring by comparison with more mathematically challenging ones, Karl stresses that he finds the qualitative problems more difficult. Moreover, Karl locates these differing degrees of difficulty not between the problems themselves, but in his own ability to solve them. Like Amos, for whom physics-style problem-solving may have been boring for him just because he's an engineer, Karl feels that there's something about him that makes him less congenial to the test and database questions than those in the homework. Another student, Louise, similarly attributed her criterion for choosing among problem-solving differences to something unique about her. Louise actually wished that Professor Davis would spend more time working problems from the database in class, because she felt that they helped her learn:

Toby: So you wish he'd spend more time with the database?

Louise: Right. I think that the problems help me a lot. If I can understand the problems, then I understand the concepts.

T: Why is that?

L: That's just how my mind thinks, I guess. I've always been like that. Like, to read physics, or to read math, doesn't do me that much good, I don't think. If I can sit down, and I can work the problems, then I can go back and read, and follow what it's meant by formulas, but if I just try to sit down and read, that doesn't do me much good I don't think.

For Louise, her preference for learning through solving the kind of problems that are on the database reflects "just how [her] mind works." She also stressed the differences between the database problems and simpler "plug-and-chug" problems, telling me that Professor Davis's "problems and his database are, there are a few that are just plug-and-chug type problems, but not many. Most of them you have to understand the concepts and how they work in order to even approach the problem. So I guess that's why it helps me to work those, and to learn that." Unlike Karl and Amos, however, Louise saw no difference between the concept-oriented approach these problems demanded and the strategies called for by good engineering problems. Instead, what varied were the concepts themselves, and it was her preference for engineering concepts that distinguished her from physics majors:

Louise: I use the same kind of problem-solving techniques [in physics as in engineering], but honestly, I don't really like physics that much. I liked it in high school, I don't know if it's this class, or that I found other things I liked better, but I don't really care for it right now. I think if you like something, then it's easier to do then if you don't like something. And it's like...kind of hard to make myself do physics, like do the problems, when I really am not, I don't really care for it, and engineering, like my chemical engineering class, I like that class, I mean I like the concepts behind it,. I like trying to figure out the problems, and I work harder at that class then I would at physics. So I guess...I don't know.

Toby: So is there also a way in which your engineering class, the problems in your engineering class, fit your style better? Do you feel like there's a difference in solving the problems besides that you like the things the problems are about?

L: Not really. Like my engineering problems, although I'm in chemical engineering, some of them have to do with chemistry, but just in this last couple weeks, it's been more like reactions and that type of stuff, and before it was just basic, like problems, like how you work a system, like a heating system, that kind of stuff. I don't see where...physics to me, it doesn't, I mean I know it has a lot to do with how the world works, like that's what it explains, but I don't guess I can really relate what I want to learn about to that, I don't think.

T: Why not?

L: I don't know why I don't...there's just something...I think my professor, he's willing to help, definitely, he's always in his office, he helps me, but it's just, I don't know. Like the class isn't made that interesting, maybe that's why I've turned against it, it's basically him deriving formulas, and I don't find that interesting at all. I think he has a hard time relating it to what's going on now, like relating it in the world, like how things work, like how new inventions are coming about, like this and that, but he doesn't...I don't think he does that very well.

Louise feels that her class, as it operates, doesn't allow her to have the kind of relationship with physics she would like. She wants to be able to "relate what I want to learn about" to what she learns in her physics class, but she doesn't feel like Dr. Davis is able to help her do that. Ironically, then, in contrast to my insistence that each of these classes is tailored to the presumed academic identity of each group of students, Louise doesn't think the class goes far enough to meet her distinct needs. "Damn it Jim," she might have scrawled on her desk once, during a particularly boring hour of derivations, "I'm an engineer, not a physicist."

The 'Physicsly Challenged'

On the first day of class in General Physics, I couldn't help my eyes from wandering repeatedly onto the notebooks of two students sitting in front of me. They were carrying on a written dialogue, writing brief notes back and forth to one another. This probably wasn't so unusual; it was a big class, and the professor certainly couldn't monitor such subversive activities. I can even remember doing it myself with a friend during my undergraduate days, in a particularly dull class. But unlike the conversation on which I eavesdropped, the exchanges I recall participating in were generated in order to allow us to escape the lecture material in favor of more interesting topics. These students' comments to one another actually focused on the course work, and on the student-identities presumed by the class. As Dr. Jones told the class, "Now we're going to review trig," the first student in front of me wrote "Is this physics for morons?" and showed it to his friend. The friend wrote back, "Yes!" As Dr. Jones gently explained the law of sines, the notebook-writers expressed their annoyance at having to sit through this remedial math lesson: "He wants us to measure? What the fuck. Law of sines? Hate this class already."

A bit further into the lecture, the professor introduced the distinction between scalars and vectors. Reminding the students of their particular status as physics learners, he told them, "in more advanced physics courses, we deal with things even more complicated than vectors, but here we just deal with scalars and vectors." Later, he pointed out a particular mathematical formulation and said, "in calculus we'd call that a derivative, but you don't do calculus." Unimpressed, my notebook-writers continued:

> "My brain has left my body"
> "Help"
> "Yes, I did graduate from high school."
> "Can we leave now?"
> "This class is special"

With this final comment, the students faced one another and shared a long, muffled chuckle. They clearly felt superior to the other students in the class, and felt that the class was directed toward less-able students than themselves. They joked that the class was "special" in the same way as "special education" or "Special Olympics"--designed for students with "disabilities" to do physics and math.

Another student in the class actually embraced this model, and named her disability. This passage follows a conversation in which she told me about dropping physics because she couldn't keep up, and because the instruction wasn't tailored to her needs. She faced a dilemma regarding whether she should try to re-take physics, a requirement for her double major in biology and wildlife science, or give up the biology major in order to avoid physics:

Toby: So physics is really in your way right now.

Molly: Very much. It is the largest obstacle in my way, believe it or not. Because if I minor in biology [instead of double-majoring], I have to take one semester of organic chem anyways, and since I'm already doing this, I have to take that for wildlife science, so I get to take survey of organic chem, but who cares. It's organic. But I mean, to minor in biology, all I need is like microbiology, and that's it. That's all I would need. I don't even need to take the physics. So the physics is really in my way, 'cause I would need to take micro anyways if I were majoring, and I would take...I only have like 15 extra credits to do the double major, so I was like, it's not that much, just a semester's work, but the physics is just really pushing me away from it a lot. It's kind of messing up my plans here. I consider it my hardest class ever. I will definitely...even probably more so than math. I don't know if it's because it's at [this university] or what, but I'm really wishing I had taken it at [the community college she transferred from].

T: Yeah, I understand. You've disliked math? I mean, you took calculus, a lot of people never get as far as taking calculus...

M: What I did is in high school I didn't realize how much I'd need it. I mean, when I was in middle school, I was always the top of the class, I was always the excelled group of students that got to take the extra things, and when I hit my freshman year in high school, I wasn't that anymore, it wasn't as big a deal. I mean I was still, like I got the advanced studies diploma, things like that. And I was always still a good student, I ended up with a 3.0 average, but I wasn't exceptional like I used to be, and once I started getting in the math, I didn't like it, so I didn't pay attention to it. Same with a lot of my biology. I know that I don't really have to study and think too much. It's easy to comprehend for me. So things that I really really have to comprehend I just toss aside, I don't want to do that, I'll do it later, so my maths were really bad. But when I applied myself in math I did well. But like first year algebra I got a D. Geometry I got a D. I slept through geometry, and they just passed me basically. But I was getting A's in other things, so they were probably looking at it and going, "well, let's just get her out of here" (laughs). My geometry teacher didn't like me because I slept in his class...but no, I never applied myself, but once I got to algebra 2 in high school, there were certain quarters that I would apply myself, certain times I didn't--I had such a bad foundation...I have to always go back and look through the book step by step and see how it's done, and then maybe say, "oh yeah, that's how to do it. And you can't do that when you're in physics, of course, cause you can't go back and look in a book during a test; you don't have that kind of time...[pauses, then smiles, laughs] I'm physically challenged...physicsly challenged.

Like the notebook-writers, Molly draws on the language of disability to articulate herself as a physics student . For her, of course, "physicsly challenged" has two meanings; it refers both to the obstacle she sees physics posing to her academic progress, and to what she understands as her own inability to learn or do physics. She draws a provocative distinction between math, in which she did well "when I applied myself", and physics, where she wasn't able to succeed despite putting in a great deal of time and effort.

Later, I asked Molly to comment more specifically about the difficulties she encountered with physics problems. Her description was revealing:

Molly: Well, I would try to do what was in the book, I would try to find something that was similar in the book. And I guess the problem with me is, you've got to know math so well, that you've got to know regular math, and then put it into physics math. And I wasn't able to do that necessarily all the time when I had a problem in front of me, to go back and take a regular math or trig-type application, make it into one particular physics equation, and then derive it into another form of that equation. That was just too much for me. And so unless it was somehow in the solutions guide somewhere, or I could get help from someone to explain it with me, there was no way I was going to be able to solve that, because [Professor Jones] never went through the steps, and you have to. We're all taking this, some of us, for the first time. You're going to have to do that. And if not, then maybe they should have a pre-physics class or something like that, because it's just impossible to go from nothing or just remembering basic trig and then, you've got to put in the physics, and derive all these different equations, it's just too hard to remember, especially on the test, when you only have half an hour, and especially when you can't have a problem set with you, and try to figure out and plug, a, v initial, and stuff like that, and so when I would go do the homework, I would run into a lot of problems with, "hey, this isn't in the book anywhere, how do I do this?" Some of the times, I'd be able to figure them out on my own, occasionally. Some were just too far out for me to do...

Molly's complaint that Professor Jones "never went through the steps" initially puzzled me, because he had, in fact, repeatedly provided students with general algorithms they could apply to their problems. But as I looked more closely at her comments, I realized that

Molly wasn't talking about a general algorithm she could follow step-by-step to a solution for any given problem, because such algorithms never dismantle the unique challenges and conceptual difficulties of a given problem. For each new problem Molly encountered, she needed a model for approaching that particular problem's idiosyncrasies. Without the "physical intuition" the major students were encouraged to develop or the goal-oriented, "plug-and-chug" solving style the engineering students were drilled in, she had to find, either in the book, in the study guide, or in the lecture, a solved sample problem similar to each new one she faced. She lacked the problem-solving heuristic that helped the major students to "think like physicists."

Before she dropped the class, Molly tried to remedy her situation by asking the professor for help. One day, while Dr. Jones was in the middle of working sample problems, Molly raised her hand and engaged him in the following dialogue:

Molly: "If you have time, can you do one of the problems in the back of the book? I can follow the examples in the book and examples in class, but I sometimes have trouble when I'm trying to do problems on my own."

Professor Jones: "Well, you know, I...very few of those problems are any more complicated than this one."

Molly: "I know, but..."

Professor Jones: "So, you know, I'm not going to work any of the problems assigned to you, so if I picked a problem that's not assigned to you, it'd be similar to me taking this problem, because they're similar to those kinds of problems. It's not the same, it's what you'll work, but if I took one that you didn't work, it'd be similar to what I picked. [chuckles] So I don't understand the problem here. I am working problems similar to what are in the back of the book. Same types of problems. I'm going to do another one right now. If there are certain problems that you don't know how to work that aren't assigned to you, of the chapter that's due next, you can always come to Monday nights [to an extra help session], or come to my office, and we'll work through any problem you want to work, as long as it's not an assigned problem, or it's already been assigned and handed in. If it's an assigned problem, I'll just talk about and not actually work it."

The nods and murmurs I saw and heard around the classroom suggested that many students shared Molly's frustration, and her dissatisfaction with Dr. Jones' response. Molly wanted Dr. Jones to work one of the problems that the students had actually been assigned as homework problems, but Dr. Jones didn't see the need to give away answers to graded homework problems when he could demonstrate the same principles with a similar problem. The two simply proceeded with entirely different assumptions about physics problems and how to solve them. For Dr. Jones, problem-solving operates on the principles of qualitative analysis and conceptual framing that follow from "thinking like a physicist." For Molly, on the other hand, every problem, because it contains a different set of quantitative operations, presents a new challenge.

Another student, Greg, commented on the differences between his approach to problems and Dr. Jones':

Toby: Before we run out of tape, any other comments on physics, physics class, anything?

Greg: I don't know. I probably wouldn't be like this [frustrated with the class] if it wasn't for the professor. It...I guess it's because he...the way he teaches is not exactly what I would consider a teacher. I mean, he's too much of a professor than a teacher. He's trying to make you do exactly what he's doing, and sometimes that won't work for you. And I myself, I do problems differently than when he does them in there. I mean I'll use different symbols and all that stuff, but if I get the answer, you know, it's my business. And he's...I think he's the kind of person that...he wants it done his way. And I don't think...he's into the groove now, and he's been here for whatever many years, and I think it's become habit to him, and he's not...I don't want to say he...he's not that bad of a teacher...he's not that bad. When I was younger...the one thing they told me that was really, they liked about me was I could see things in three dimensions, and if it wasn't for the math, I would love physics a lot more, because I can look at things, I can look at something, and if given a problem, if you say something to me, I can picture it three dimensionally in my mind. I can look at something like a...I can play it back...not that I have a photographic memory, it's just that I can look at things, with a real 3-dimensional mind, and I think that helps a lot with physics, especially in more than 2 dimensional problems, being able to look at something and to tell which way it's going to go, and how forces are acting on it, things like that. It would, I think that helps a lot for physics. And that's probably why I do like it, because it allows me to use my mind some.

At least three key points leap out of Greg's comments. First, he distinguishes between a professor and a teacher, complaining that Dr. Jones is too much of the former and not enough of the latter. In sharp contrast to Matthew, the physics major who felt Dr. Smith was a good teacher *because* he was a good physicist, Greg sees Dr. Jones' tendency to perform as a physicist as conflicting with his ability to communicate the material effectively to non-majors, students who didn't intend to adopt the professor's professional identity. Like Molly, who struggles to make connections from one problem to the next, Greg doesn't find Dr. Jones' ways of conceptualizing problems congenial to his own, and he wants to use his own framework to make sense of problems. The second point follows from the first: while, as a good physics professor, Dr. Jones modeled just the kind of approach to problems that a physicist ought to employ, Greg had no intention of becoming a physicist, and he was content to take his own approach to problems. Third, and most critically, Greg stresses that he does bring a degree of physical intuition to his problems, that he can visualize the real physical situation associated with a problem--he does possess some "expert" skills, and could very well be a successful physicist if he were a stronger mathematician. At another point, he told me even more succinctly, "that's the only reason I wasn't a physics major, because I knew I couldn't handle the math."

To get at the specific dimensions of Greg's difficulty with the math of physics problems, I asked him to talk about the places where he had to solve problems--in weekly homework sets and quizzes:

Greg: I've got a 68 or 70 average on the quizzes, and then in the homeworks I've gotten like 75 or something like that...It's because the tests, the quizzes themselves are...some of those problems...like he didn't, on the one I remember, there was a block moving, an object moving to the right, with a certain velocity, and then a force acts on it this way, and unless you actually asked him the question, you didn't...you couldn't...the way the problem was worded, you couldn't understand if there were other forces acting on it, or it was just that single force, or what it was. So afterwards, I went up and asked him, and he's like, "all the information is in the problem." And I went, "whoa. That's why I'm asking you the question, because I don't understand the problem." And he just...he's done that to me several times. I've gone up to him and asked him, and he's like, "the information is in the problem." And he tells you, "if you have any problems, come up and see me." Well, he doesn't help you if you go and see him.

Toby: So...you feel like a lot of the problem was just poor wording and stuff like that, that the questions were just too...

G: Yeah. It's almost like sometimes he puts trick questions on there, so...like he's trying to word the problems so we can't figure it out. I've talked to a lot of people in the class, cause a lot of them, a couple of them are in my physics lab, and I know them pretty well, plus I know a few other people, all the cadets in the class. We all talk about it. Everybody more or less feels that he goes too fast, and his quizzes, the wording on them is just terrible. None of them...most of the problems that I have problems with, most everyone I talk to is like...I didn't understand the question, I didn't understand the problem.

Greg's description of a quiz problem that gave him trouble puts a new spin on the novice's problem-solving struggles. He understood that in the problem, as some object moved to the right, a force was brought to bear on the object in a direction perpendicular to its original motion. But he wasn't sure whether he could assume that the initial motion of the object was of uniform velocity, and thus unaffected by any other net force; the object could have been accelerating to the right under the impulse of some propelling constant push or resisting force of friction. It wasn't that he couldn't conceptualize the physical scenario, but rather that he wasn't sure what kind of disciplinary agency he was to submit to, what bridging moves he should make between the formulation of the problem on the quiz and the physical picture it described. He was left feeling like the question was designed to trick him, and yet the professor insisted that he had all the information that he needed. Later, I asked Dr. Jones about these struggles as students had described them to me:

Dr. Jones: Well that's a common problem human beings have is taking words and putting them into equations. Word problems have always given people problems, and physics problems are always word problems. But I keep emphasizing to students early in the course that there are a lot of implied things in problems. It doesn't always tell you x is 5 and y is 6. It might say the particle starts off at rest, and various things like that, and you have to read and imply certain variables, values, without being explicitly told what they are, just by knowing what the words mean. And that's hard for some students, to figure that out. Particularly because as you move from one subject matter to another, the words are different, and the way you describe things, and what you mean by various words, and it just takes them a while to get the vocabulary.

In other words, students like Greg and Molly have trouble figuring out the particulars of various problems because they don't speak the language, because they lack the vocabulary. Thinking like a physicist, then, has a semantic dimension; making leaps of physical intuition requires a level of familiarity with the ways problems are formulated. But these students aren't learning to think like physicists. They don't, unlike Matthew, develop a familiarity with the range of problem-types they might encounter by solving all the problems in a chapter, assigned or not, just to learn to interpret more physical situations. And they don't have stressed to them and explicitly modeled for them the "way

I would look at a problem" by a good physicist-teacher, because they're just learning how to follow the steps, get the concepts, plant the equations in their short-term memories so they can recall them for the quizzes, and pass the course. Greg and I continued:

Toby: So they're a lot worse than the homework problems, you're not running into the kind of problems in the homework that you are on the quizzes?

Greg: No, it's the quizzes that are hurting me. I can do the...homework problems are like, ho-hum, I've got this, I've got this. But when he gives the quiz, I'll look at it and go, "This is nothing like what we've gone over. I don't remember this." I'll look at the problem, and, I mean, I'll study, I'll study for it, get up there in class and go, "this wasn't in the notes" you know, or I'll look at, I'll write down...I've written down a couple of the problems, and when I go and look at the answers, when he posts them, I don't remember, you know? You didn't teach us that, you didn't teach us that, you didn't say anything about that...He knows...on a couple of problems, expects us to remember a lot of conversion factors, and stuff like that. I know I don't know how to convert...he doesn't say we have to memorize it. He never tells us what formulas we have to memorize. Well, when we get to class, we're expected to know certain exact ones that are...and we're not allowed to bring any conversion factor sheet with us. I can memorize things pretty well, but if I don't know what to memorize, and I'm not going to memorize the whole sheet...I've got other things I have to do.

Greg's "other things" he has to do sum up the difference between him and a physics major--he has his own major, biochemistry, to worry about. Another student, Curtis, similarly puzzled over the amount of memorization expected of him in the course:

Curtis: So far, it's not too bad. In fact, I shouldn't say I don't remember anything from high school because I do remember a little bit, now, but this basic stuff we're doing. I find it kind of confusing, with all the equations we seem to be getting thrown at [us], all of a sudden. I mean, right away there's a lot to memorize. And it kind of seems like, uh, I mean, we're supposed to memorize all these equations, but I don't think I'm going to remember them after I graduate, you know.

Toby: Right. Or maybe even after your test?

C: Yeah. So it's kind of like, I don't know why we don't...somebody brought up a question about...lists of equations, you know, for a test and I thought, you know, it's probably better off knowing how to use the equations than actually memorizing them because I don't think I will. And he said...and the professor said for the final we'll do that. So it kind of seems you know...why. But so far it's not too bad, pretty straightforward. But I expect it to get a lot worse (laughs).

Both Curtis and Greg feel like they are expected to memorize too many equations, and that memorizing them comes at the expense of really understanding the material. They bristle at both the stifling restrictions and the unreasonable expectations the curriculum imposes upon them--they are at once frustrated that they are limited to memorizing equations rather than exploring concepts, and intimidated by the amount of material they have to memorize. The following comment from Molly effectively synthesizes these General Physics students' problem-solving and memorizing frustrations:

Toby: When you distinguish between regular math and physics math, you meant by physics math, the equations, essentially, and once you had to get into dealing with the equations...

M: Basically, yeah, you have you know, regular trig, regular calculus, and everything, you've got to know that down pat before you can ever imagine taking that and applying it in a physics equation, I feel. And if you're not extremely strong in it, or you don't know everything, then it's very hard. I just took a calculus class where I taught myself. It was a class over the summer. It was the hardest class I've ever taken in my life, because I had to teach myself the book, and go in and take tests that someone else prepared, that didn't know what I had taught or comprehended from the book. I mean, I spent hours, hours, like 10 hours a week on this class. I mean, I had to, like, not go to work the last week of the class so I could make up the rest of these tests, and I ended up getting a C in there. And to me, I felt I should have gotten all these A's. So I have like calculus, some of it right there, but still, if you go and you ask me how to do this, this and that, I'm not going to remember. It's not going to be right there, and there's no way, even if you do a 5-page review that's in the back of the physics book, there's no way that you're going to be able to remember all of that trig, from years and years and years. It's impossible. I don't know if I just don't have that kind of mindset, that I'm going to remember all of those equations, and how to do everything, but there's no way. I've never had that kind of scientific mindset, I think. That's why maybe I've always liked biology. But I just can't remember how to do everything, and then when I have to go ahead, and remember it, then take it into a physics equation, it's kind of hard. I mean, don't get me wrong. Some of the physics stuff we were doing is quite easy, like when you get into similar triangles--when he's not explaining to you how to do it, or there's different variations of it, like 5 or 6 every time, it's very hard. And you just have to dedicate so much--that's the thing. You just have to--to really understand physics, it would be essentially like you're teaching yourself, like this math class I took, And I know how much time I devoted to that. I neglected...I took regular chemistry this summer as well. I neglected that as well. So you're neglecting everything else to do the physics. You're not doing a good enough job in anything, because you're all pulling. Right now, like I said I'm suffering because I took so much time out to do physics first portion of the semester. My genetics, I failed my first genetics test. He has to turn in an F for me, as a transfer student. He got a listing, and it was because I got so behind from the beginning of the book, I was doing physics. I mean, I'm sure along the line somewhere, I'm making excuses, I could have done something, but ultimately, I was still doing very bad in physics, which meant I didn't have enough time to do stuff in there either. I don't know if it's because like I said, because I haven't taken physics before, or I don't have a very strong math foundation, but I mean I've taken all the calculus courses, you know, applied calculus, I've taken trig, I just think if you have the basic knowledge, you should be able to get through a general physics class.

As Molly points out, she makes excuses for her struggles with physics. In fact, she locates the source of her difficulties in several different places--first in the difficulty of the class itself, then alternately in her own lack of a "scientific mindset", in her inability to dedicate all of her time and energy only to her physics course, and in her inadequate math foundation. Ultimately, she doesn't know where to place the blame for her failure, and she puzzles over her sense that, contrary to her own experience, someone with her background "should be able to get through a general physics class." She can't settle on a good reason why she shouldn't have been able to fit into the class, to be a successful general physics student, and yet she remains painfully aware that she tried and failed once, and that if she can't try again and succeed, she'll have to give up her goal of a double-major. She summed up what succumbing to this obstacle would mean for her: "I really don't want to give up my goals, 'cause it makes me feel like I'm giving up something, I'm giving up part of my goal, my life. And I'm a really big dreamer...with the physics it's like I have nowhere to turn."

So are Molly, Greg, and Curtis really 'physicsly challenged'--victims of some innate inability to handle the rigors and abstractions of physics? Or does the General Physics curriculum saddle them from the outset with presumptions of physics mediocrity? I hope the stories in this section make it clear that neither of these hypotheses adequately accounts for the experiences of the students I spoke to. Rather, I repeat my insistence that we can only make sense of each of these sets of students and their respective physics classes in terms of a complex 'mangle' of educational practice. So in other words, I conceptualize the disciplinary student 'selves' of these classes as the products that result when a flow of hundreds of diverse students is ushered through only three narrow channels into learning physics: some slide smoothly through one of the available routes, some splash against a partition before being funneled through, and some simply get lost in the turbulence or crash against the dam. Who they are as physics learners gets delineated both by their own motivations, capabilities, enthusiasms, ennuis, and so forth which drive their experiences, and by the curricular forces and cultural patterns that constrain those experiences. And those physics-learner selves are only slices from among conglomerations of selves that attend each student; selves are, as Kondo puts it, "constructed in the plural." To make sense of selves, then, we must do what I have attempted here--to track the activities and experiences of humans as they, as we, negotiate with various sites, circumstances, communities, knowledges, and so on to constantly engage in constructing, deconstructing and reconstructing our selves.

Conclusion:
Applying the Solutions

The Final Prayer

And it came to pass, that early in the morning of the last day of the semester, there arose a multitude smiting their books and wailing; and there was much weeping and gnashing of teeth; for the day of judgment was at hand, and they were sore afraid. For they had done those things which they ought not to have done, and they had left undone those things which they should have done..., and there was no help for it.

And there were many abiding in the dorm who had kept watch over their books all night, but it naught availeth. But there were some who arose smilingly, for they had prepared for themselves the way, and made straight the path of knowledge. And these wise ones were called the curve-breakers. And the multitude arose and ate a hearty breakfast.

And they came unto the appointed place, and their hearts were heavy within them. And they came to pass, but some passed out. And some of them repented of their riotous living, and bemoaned their fate. But they had not a prayer. And at the last hour, there arose among them one known as the professor, he of the diabolical smile, and passed papers among them, and went upon his way. Many and varied were the questions asked by the professor, but still more varied were the answers which were given, for some of his teaching had fallen upon fertile minds, others had fallen upon semi-fertile, while still others had fallen flat. And some there were who wrote for one hour, others wrote for two, but some turned away sorrowful. And of these, many offered up a little bull, as sacrifice, in hope of pacifying the professor, for these were the ones who had not a prayer. And when they had finished, they gathered up their belongings, and went quietly away, each in his own direction, and each vowing to himself in this manner: "I shall not pass THIS WAY again." But it is a long road that has no turning.

---by an unknown Physics I Professor

This rather lengthy epigraph was sent to me as I revised this final thesis draft, and it seemed too fitting to exclude. It was forwarded to me by email from a friend at another university; he is taking an introductory physics class this semester (he's a pre-med student at a smaller university that doesn't match the array of different beginning physics sequences offered by the school that hosted my fieldwork), and this charming piece was sent around among students in his class as the final exam drew near. I find it a particularly useful piece from which to step back and survey the introductory classroom territories I've endeavored to map out, and to attempt to draw together a few conclusions.

The "Final Prayer" reveals at least two interesting assumptions about learning physics. The first, by now well-worn, idea is that some students are simply born to do physics, to be "curve-breakers." Granted, they must have "prepared for themselves the way, and made straight the path of knowledge," but that only follows from their wisdom, and places them on "a long road that has no turning," a destiny for a physics career which they cannot escape. The second provocative notion is that the success or failure of learning in introductory physics depends upon whether the seeds of knowledge were sown on fertile, semi-fertile, or barren minds; learning is, in other words, a function only of the congeniality of a given student's mind to the concepts transmitted through the professor's teaching.

In chapter one, I promised that from the interplay between the three distinct curricula of chapter two and the three distinct sets of students in chapter three, three different 'physics' would emerge.[6] And in my fieldwork, and, I hope, in chapter two, they did. Foundations of Physics appeared as a site for teaching physics majors how to behave as physicists, for endowing them with physical intuition and familiarizing them with the conceptual schema of the discipline; Principles of Physics roped off an arena for struggles over knowledge between physics and engineering, played out in the tensions between the instructors' understanding of their inspired and intuitive connections to physics and their engineering students' more practical, detail-oriented relationship to the material and its applications; General Physics served both to connect physics to those students whose lives it might otherwise not touch, and to remind those students of the restrictions that would always apply to their potential relations with physics.

Thus I really did trace three distinct 'physics', one that opened up the world to conceptual and mathematical analysis, one that offered conceptual tools for doing work in the world, and one that only pointed its students to the tools with which *others* might make sense of the world. But to adopt these distinctions, I had to insist on speaking about the classes in different terms from those of the professors, who assured me that the courses taught the same content, the same physics, and differed only in the mathematical

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[6]I considered various unwieldy configurations of suffixes and arrangements of apostrophes with which I might more tidily pluralize "physics", but in the end decided to retain the singular, asking the 's' to work overtime to denote the plural. I'm attached to this awkard construction because it encapsulates the tension between the monolithic knowledge center that structures ordinary discourse about physics, and the multiple spheres of activity I describe. I mean to problematize the quantity, to have physics be at once singular *and* plural, because that best summarizes the physics of this ethnography; physics is both the thing that all of these students study, and three different things that these different classes of students study.

sophistication they expected from their respective students. And to maintain the distinctions in chapter three, I had to struggle to keep my framework in line with that of students who articulated their diverse experiences in terms of a uniform and monolithic physics to which some bowed in reverence and committed their lives, from which others cowered in fear and self-doubt, and in face of which still others simply yawned in utilitarian disinterest.

So in a way, my three-physics framework is simply an artifact of my analysis; after all, differences and distinctions were what I went in search of when I began the fieldwork. But I don't apologize for that artificiality. It follows not only from my vantage point as comparative ethnographer, from whence I of course saw three different fields of activity emerge from three different configurations of people, texts, spaces, and schedules; but also from my situation as *concerned* ethnographer, from which I sought a way of talking about the students that didn't simply separate them into better and worse learners of a uniform physics, more and less skilled practitioners of mathematics, and so on. Moreover, as indicated by the extent to which my data and my argument do suggest multiple 'physics', a uniform, singular, and monolithic physics is likewise an artifact of the professors' and students' position within the disciplined discourse of physics proper.[7]

I call myself a "concerned ethnographer" in order to remind myself that I am deeply concerned with the stakes of my anaylsis--what is at stake in learning physics for the students I observe, interview, and write about, and what is at stake when I study them. To address the latter set of stakes, I have to confront the possibility for strategies with which I might, through my work, intervene in physics education. I have stressed that issues of identity and selfhood sit at the center of my analysis; I have explored ways in which presumptions about students' identities have consequences for those students' circumstances for learning physics, and in which those circumstances have consequences

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[7]Thanks to Marianne de Laet for helping me to articulate this point in terms of the artifacts of analyses.

for students' understanding of themselves. My attachment to the language of three different 'physics' follows from my concern with identity.

I won't pretend that this analysis reveals obvious "solutions" for the problems that might attend introductory physics education. But I do think I have pointed to some useful possibilities. I have tried throughout this text to show how identity matters for physics instruction--how assumptions about who students are constrain their relationships with physics, and how their relationships with physics impact who they are. What this analysis suggests to curriculum developers and instructors should be obvious: that the ways students understand themselves, and the ways the curriculum and its implementers understand students, demand consideration alongside issues of cognitive content and mathematical depth in physics courses.

So does this study indicate that a range of introductory physics sequences is inherently a bad thing? I don't think so. Students, after all, are different, and they have different wants, needs, predilections, and expectations for physics. Moreover, homogenized introductory courses seem likely to continue to replicate the agonies of the "final prayer" epigraph, in which a few might be curve-breakers, but the rest will be doomed to weeping, wailing, and gnashing of teeth. Instead, I want to urge physics departments to foreground the differences in their various students' trajectories through physics. Rather than being swept under rugs of math preparation and language of common course-goals, issues of identity should be made central and explicit in discussions about curriculum. Rather than emphasizing "thinking like a physicist" for all students, the curriculum should be opened up to the possibilities of different relationships with different 'physics' to accommodate the needs and wants of different students.

Granted, these suggestions sound starry-eyed at best. But they needn't be so far-fetched. One of my General Physics students, Greg, told me a story that demonstrates one way in which a student with no illusions of becoming a physicist might nonetheless chart his own course through physics, and articulate a way of building physics into his own life that accommodates his own needs, abilities, and desires:

Greg: Personally, I've really been interested in the theory of relativity a lot. See, I had a student teacher in high school who happened to be...right before she came to the high school she studied the theory of relativity. So one day, she sat down, and she went through and explained the general principle behind it, and I said "Wow, that's really interesting" and how time slows down as you speed up, and all that stuff, and I was like, "Hum." So I went ahead and studied it. I went and, you know, checked out some books, read through, and...I don't want to say researched it, but learned more about it. So...and then when I...I mean, now when I look at...I didn't look at different things in a physics type of thing, you know, if I apply a force in this way, to get it to go...it comes in handy in pool, too...it's helped my pool game...my ability to aim has improved a lot (I laugh). It also...billiards also helped me with physics, because it gives me a three-dimensional look at what happens. It's almost like an experiment for me. So whenever I shoot pool, I'm always thinking about the physics of it, too. It's kind of strange, but it works.

So by finding his own path into physics, Greg was able to transcend the limits the curriculum might have otherwise placed on him. Greg's textbook cover showed him only that snow boarding, like pool, and so many other activities he might participate in, is subject to the laws of physics; it did not supply him with vector arrows and mathematical tools that he might actually mobilize to engage the physical world. But Greg nonetheless succeeded in finding his own way to draw physics into his life and his activities. And, of course, he didn't do it alone; he relied on the guidance of a teacher who found a way to foster Greg's interest in physics without constraining him to a particular set of terms in which he must engage it. Jim Garrison has named the tool such a teacher must draw on to imagine the potential for unique and productive relationships with knowledge "practical wisdom": "Only such wisdom can enable teachers to create ethereal things and to recognize when their students do so as well. Wise teachers must see the possible beyond the constraints of the actual." (1995: 428) Perhaps by opening discussions of curriculum up to issues of identity, and drawing on a little practical wisdom, physics instructors might imagine new ways of constructing introductory classrooms that don't turn any students into the "physicsly challenged."

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