CHAPTER 3

There's More Than Content to a Physics Course: The Hidden Curriculum[1]

Education is what survives
when what has been learned
has been forgotten.
B. F. Skinner
(*New Scientist,* 21 May 1964)

In the last chapter, we discussed how our cognitive model of student thinking helps us understand the importance of the ideas our students bring into the classroom. But cognition is complex. Students do not only bring ideas about how the physical world works into our classrooms. They also bring ideas about the nature of learning, the nature of science, and what it is they think they are expected to do in our class. In addition, they have their own motivations for success. We are often frustrated by the unspoken goal of many of our students to be "efficient"—to achieve a satisfactory grade with the least possible effort—often with a severe undetected penalty on how much they learn.

Most of my students expect that all they have to do to learn physics is read their textbooks and listen to lectures. Although some students who believe this don't actually carry out this minimal activity, even those who do often fail to make sense of physics in the way I want them to. This leads me to believe that reading textbooks and listening to lectures is a poor way of learning for most students. Sagredo objects, "This is clearly not universally true!" Remembering Principle 4, I concur. As physics teachers, most of us have had the experience of having a few "good" students in our lectures—students for whom listening to a lecture is an active process—a mental dialog between themselves and the teacher. Indeed, many of us have

[1] This chapter is based in part on a paper by Redish, Saul, and Steinberg [Redish 1998].

been that good student, and we remember lectures (at least some of them) as significant parts of our learning experience.[2]

A similar statement can be made about texts. I remember with pleasure working through some of my texts and lecture notes, reorganizing the material, filling in steps, and posing questions for myself to answer. Yet few of my students seem to know how to do this or even that this is what I expect them to do. This leads us to think about an additional observation.

Many of our students do not have appropriate mental models for what it means to learn physics.

This is a "meta" issue. People build schemas not only for content but also for how to learn and what actions are appropriate under what circumstances. Most of our students don't know what you and I mean by "doing" science or what we expect them to do. Unfortunately, the most common mental model for learning science in my classes seems to be:

- Write down every equation or law the teacher puts on the board that is also in the book.
- Memorize these, together with the list of formulas at the end of each chapter.
- Do enough homework and end-of-the-chapter problems to recognize which formula is to be applied to which problem.
- Pass the exam by selecting the correct formulas for the problems on the exam.
- Erase all information from your brain after the exam to make room for the next set of materials.

I call the bulleted list above "the dead leaves model." It's as if physics were a collection of equations on fallen leaves. One might hold $s = \frac{1}{2}gt^2$, another $\vec{F} = m\vec{a}$, and a third $F = -kx$. Each of these equations is considered to have equivalent weight, importance, and structure. The only thing one needs to do when solving a problem is to flip through one's collection of leaves until one finds the appropriate equation. I would much prefer to have my students see physics as a living tree.

A SECOND COGNITIVE LEVEL

The issues discussed in the introduction to this chapter seem to be at a different level of cognition than the more specific cognitive responses discussed in chapter 2. A number of cognitive researchers have identified a second level of cognition that resides "above" and controls the functioning of the level described in chapter 2 [Baddeley 1998] [Shallice 1988] [Anderson 1999]. Many of them refer to this as *executive function*—thinking processes that manage and control other thinking processes. In the context of instruction, three types of cognitive controls are particularly important: expectations, metacognition, and affect.

Each student, based on his or her own experiences, brings to the physics class a set of attitudes, beliefs, and assumptions about what sorts of things they will learn, what skills will be required, what they will be expected to do, and what kind of arguments and reasoning

[2] However, compare my discussion of one of my lecture experiences in the section of chapter 7 on "The Traditional Lecture."

they are allowed to use in the various environments found in a physics class. In addition, their view of the nature of scientific information affects how they interpret what they hear. I use the phrase *expectations* to cover this rich set of understandings that are particular to a given class. *Metacognition* refers to the self-referential part of cognition—thinking about thinking. Sometimes these responses are conscious ("Wait a minute. Those two statements can't be consistent."), but the term is also used to refer to the unconscious sense of confidence about thinking ("It just feels right."). Under *affect*, I lump together a variety of emotional responses including motivation, self-image, and emotion.

EXPECTATIONS: CONTROLLING COGNITION

Expectations affect what students listen to and what they ignore in the firehose of information provided during a typical course by professor, teaching assistant, laboratory, and text. They affect which activities students select in constructing their own knowledge base and in building their own understanding of the course material. The impact can be particularly strong when there is a large gap between what the students expect to do and what the instructor expects them to do.

Most physics instructors have expectation-related goals for their students, although we don't often articulate them. In our college and university physics courses for engineers, biologists, and other scientists, we try to get students to make connections, understand the limitations and conditions on the applicability of equations, build their physical intuition, bring their personal experience to bear on their problem solving, and see connections between classroom physics and the real world. Above all, we expect students to be *making sense* of what they are learning. I refer to learning goals like these—goals not listed in the course's syllabus or the textbook's table of contents—as part of the course's *hidden curriculum.*[3]

Expectations about learning

Students' expectations about how and what they will learn in science classes have been studied all across the curriculum. For pre-college, many studies have demonstrated that students often have misconceptions both about the nature of scientific knowledge and about what they should be doing in a science class.[4] Other studies indicate some of the critical items that make up the relevant elements of a student's system of expectations and beliefs. I focus here on studies at the college and secondary levels.

Two important large-scale studies that concern the general cognitive expectations of adult learners are those of Perry and Belenky et al. [Perry 1970] [Belenky 1986]. Perry tracked the attitudes of Harvard and Radcliffe students throughout their college careers. Belenky et al. tracked the views of women in a variety of social and economic circumstances. Both studies found evolution in the expectations of their subjects, especially in their attitudes about knowledge.[5] Both studies found their young adult subjects frequently starting in a *binary* or *received*

[3] The first use of this term that I know of is [Lin 1982].

[4] See, for example, [Carey 1989], [Linn 1991], and [Songer 1991].

[5] This brief summary is an oversimplification of a complex and sophisticated set of stages proposed in each study.

knowledge stage in which they expected everything to be true or false, good or evil, etc., and in which they expected to learn "the truth" from authorities. Both studies observed their subjects moving through a *relativist* or *subjective* stage (nothing is true or good, every view has equal value) to a *consciously constructivist* stage. In this last, most sophisticated stage, the subjects accepted that nothing can be perfectly known, and they accepted their own personal role in deciding what views were most likely to be productive and useful for them.

Although these studies both focused on areas other than science,[6] Sagredo and I both recognize a binary stage, in which students just want to be told the "right" answers, and a constructivist stage, in which students take charge of building their own understanding.[7] Consciously constructivist students carry out their own evaluation of an approach, equation, or result, and understand both the conditions of validity and the relation to fundamental physical principles. Students who want to become creative scientists will have to move from the binary to the constructivist stage at some point in their education.

An excellent introduction to the cognitive issues involved in student expectations is given by Reif and Larkin, who compare the intellectual domains of spontaneous cognitive activities that occur naturally in everyday life with those required for learning science [Reif 1991]. They point out that an important component of executive function is "deciding when enough is enough." They note that knowledge in the everyday domain is very much about *satisficing* rather than optimizing.[8] The kind of consistency, precision, and generality of principles typical of scientific knowledge is neither necessary nor common in people's everyday activities. Students often apply everyday-domain thinking when we want them to apply scientific-domain thinking.

The structure of student expectations: The Hammer variables

In order to get a handle on the complex issues of executive control and expectations, we need to begin defining specific characteristics so that we can talk about them and begin to think about ways to further them with instruction. In a series of interesting papers, David Hammer has begun this task [Hammer 1996a] [Hammer 1996b] [Hammer 1997]. In these papers, he identifies a number of parameters that arise from the expectations that a student brings into the physics class. Hammer's three variables are listed in Table 3.1.

I refer to these attitudes as *favorable* or *unfavorable*, since to make reasonable progress toward becoming a scientist or engineer, a student will find unfavorable attitudes limiting and will have to make a transition to the attitudes listed in the favorable column.

Sagredo complains, "I certainly expect my students to have the attitudes that you call favorable when they enter my class. If they didn't learn these attitudes in school, what can I do about it?" One of the problems, Sagredo, is that we often actually encourage unfavorable attitudes without really being aware of it. While working on his dissertation, Hammer did a case study with two students in algebra-based physics at Berkeley who were carefully matched

[6] Perry specifically excludes science as "the place where they *do* have answers."

[7] In my experience true relativism is rare, but not unheard of, among physics students.

[8] The term "satisfice" was introduced into economics and cognitive science by Herbert Simon, who won a Nobel Prize for the work. The point is that in real-world situations people do not optimize. It takes too much effort. Rather, they tend to seek an answer that is "good enough," that is, one that is both "satisfactory and suffices." This creates implications for the variational principles that economists construct.

TABLE 3.1 The "Hammer Variables" Describing Student Expectations [Hammer 1996a].

	Favorable	Unfavorable
Independence	takes responsibility for constructing own understanding	takes what is given by authorities (teacher, text) without evaluation
Coherence	believes physics needs to be considered as a connected, consistent framework	believes physics can be treated as unrelated facts or independent "pieces"
Concepts	stresses understanding of the underlying ideas and concepts	focuses on memorizing and using formulas without interpretation or "sense-making"

as to grade point average, SAT scores, etc., but who had decidedly different approaches to learning physics [Hammer 1989]. The first student tried to make sense of the material and integrate it with her intuitions. She didn't like what she called "theory" by which she said,

> It means formulas . . . let's use this formula because it has the right variable, instead of saying, OK, we want to know how fast the ball goes in this direction. . . . I'd rather know why for real.

The second student was not interested in making sense of what she was learning. For her, the physics was just the set of formulas and facts based on the authority of the instructor and text. Consistency or sense-making had little relevance.

> I look at all those formulas, say I have velocity, time, and acceleration, and I need to find distance, so maybe I would use a formula that would have those four things.

Student A was able to make sense of the material for the first few weeks. Soon, however, she became frustrated, finding it difficult to reconcile different parts of the formalism with each other and with her intuition. Eventually, she compromised her standards in order to succeed. Student B's failure to seek consistency or understanding did not hurt her in the course.

This small example indicates that we may inadvertently wind up encouraging students to hold unfavorable attitudes. After learning about these issues, I tried to change the way I taught in order to change this situation. How one might do this is discussed in chapter 4 on homework and testing and in chapter 5 on surveys and assessing our instruction. I used the Maryland Physics Expectations Survey (MPEX) we developed to test student expectations (described in chapter 5 and given on the Resource CD). Although at first I didn't get improvement, I learned that at least my grades were somewhat correlated with the results on my survey, whereas those of my colleagues were not. This can be taken in two ways: Either my survey is not measuring something we want students to learn, or our grades are not measuring those behaviors we want to encourage.

As we begin to develop a more complex view of what is going on in a physics class, what we want the students to get out of it, and what we value, we begin to realize that sometimes "the right answer" is not the only thing we should be looking for. A dramatic demonstration of student variability on attitudinal issues and how these issues play out in a classroom setting is given by Hammer's analysis of a discussion among a teacher and a group of high school students trying to decide whether a ball rolling on a level plane would keep moving at a constant speed [Hammer 1996a]. The students had been told Galileo's arguments that under ideal conditions it would do so.[9] I've numbered the lines in the discussion so that we can refer to them later.

1. Prior to this moment, the debate had mostly focused on the question of whether it is friction, gravity, or both that causes the ball to slow down. The students also debated whether it is appropriate to neglect friction or gravity, or both, and whether it is possible to neglect one without neglecting the other.

2. About 20 minutes into the debate, Ning argued that Galileo's ideal conditions would mean no forces on the ball, including no friction and no gravity; and, she claimed, "*if you don't put any force on it, it's going to stay still or go at constant speed*." Bruce elaborated on Ning's statement, adding that there must be a force to make the ball move:

3. *Bruce:* If there is no gravity and no friction, and there is a force that's making it move, it's just going to go in a straight line at a constant speed. . . . What's making the ball move?

4. *Amelia* [over several other voices]: The forces behind it.

5. *Susan:* He [Galileo] said there was no force.

6. *Bruce:* If there's no force pulling it down, and no force slowing it down, it would just stay straight.

7. *Harry:* The ball wouldn't move.

8. *Jack:* There's no force that's making it go.

9. *Steve:* The force that's pushing it.

10. *Bruce:* The force that's pushing it will make it go.

11. *Jack:* Where'd that force come from, because you don't have any force.

12. *Steve:* No there is force, the force that's pushing it, but no other force that's slowing it down.

13. Many voices at once, unintelligible. Sean says he has an example.

14. *Teacher:* Sean, go ahead with your example.

15. *Sean:* If you're in outer space and you push something, it's not going to stop unless you stop it.

16. *Teacher:* If you're in outer space and you give something a push, so there's a place with no gravity—

17. *Sean:* No gravity, no friction.

18. *Teacher:* —it's not going to stop until you stop it. So Penny what do you think about that?

[9] Student names are pseudonyms.

19. *Penny:* But we talked about the ball on [a surface], but when we talk about space, it's nothing like space. So I was just saying that gravity will make it stop.

20. Amelia objected to Sean's example for another reason, saying that something moving in space will still stop.

21. *Amelia:* No. Maybe there's no gravity and no air there, but there are other kinds of gases that will stop it.

22. *Teacher:* But those are other, those are outside things.

23. *Amelia:* The outside friction should stop it.

24. *Bruce:* That's not, that makes it an un-ideal state.

25. *Scott:* Space is a vacuum. Like a vacuum there's no—

26. *Amelia:* There are other kinds of gases.

27. [Several voices, unintelligible.]

28. *Harry:* We're talking about ideal space. (students laugh)

29. I intervened at this point to steer the discussion away from the question of whether there are gases in space and toward the question of whether there is a "force that's moving" the ball.

30. *Teacher:* . . . So how can one side say there are no forces on it, and the other side say there is a force that's moving it.

31. *Bruce:* Well there was an initial force.

32. *Susan:* There's an initial force that makes it start, giving it the energy to move.

In analyzing this discussion, Hammer identifies half a dozen perspectives that could be used to evaluate the students' responses. I want to focus on four.

- *Content answer:* Does the student have the correct answer?
- *Reasoning:* Does the student display a common naïve conception? Is it related to a reasoning primitive?
- *Coherence:* Does the student understand that scientific laws are developed to unify a wide variety of circumstances and that science should be consistent?
- *Understanding idealizations:* Can the student see the relevance of idealized or limiting conditions?

In the dialog, Ning gave the correct answer (line 2) but did not participate in defending it. The discussion revealed that many of the students had the common naïve conception represented by the facet "motion is caused by force" (lines 3, 8, 11, 12). Almost all of the discussion was by claim and counterclaim without citing reasoning or evidence. The discussion in lines 15–19 shows a distinction between Sean, who is trying to make a link between two rather different physical situations, and Penny, who wants to keep them separate. This can be interpreted as a difference in their understanding of the need for coherence in science. Sean's claim in line 15 tried to take the analysis to an idealized situation, without gravity or friction. Amelia (lines 23 and 26) did not appear to be comfortable in thinking about the simplified example.

In other examples cited by Hammer, students gave the correct answer to a problem, but argued its validity by citing the text or teacher and being unwilling to think about the issue for themselves.

These examples illustrate the complexity of our hidden curriculum and show how we can begin to think both about what the student is bringing in to our classes and what the student can gain from our classes in a more sophisticated way than just "are they giving the right or wrong answers."

Connecting to the real world

Although physicists believe they are learning about the real world when they study physics, the context dependence of cognitive responses (see chapter 2) opens another possible gap between faculty and students. Most students seem to believe that physics is related to the real world in principle, but a significant fraction also believe that what they are learning in a physics class has little or no relevance to their personal experience. This can cause problems that are both serious and surprising.

Even if our students develop strong concepts related to real-world meanings, the strong context dependence of the cognitive response makes it particularly easy for students to restrict their learning in physics classes to the context of a physics class. This seems unnatural to Sagredo. "Practically every problem I assign for homework or do on the board involves some real-world physical context." True, Sagredo. But that doesn't mean that students will easily or naturally make the connections that you do.

When an instructor produces a demonstration that has been "cleaned" of distracting elements such as friction and air resistance, the instructor may see it as displaying a general physical law that is present in the everyday world but that lies "hidden" beneath distracting factors. The student, on the other hand, may believe that the complex apparatus is *required* to produce the phenomenon and that it does not occur naturally in the everyday world, or is irrelevant to it. A failure to make a link to experience can lead to problems not just because physics instructors want students to make strong connections between their real-life experiences and what they learn in the classroom, but because learning tends to be more effective and robust when linked to real and personal experiences.

Even worse, students' failure to connect their personal experience to what is happening in their physics class can put up barriers to understanding that grow increasingly impenetrable. As discussed in chapter 2, multiple representations are used in physics in order to code knowledge in a variety of interlocking ways. A critical element in all of them is the map to the physical system. An essential part of solving a problem is understanding what the real-world version of the problem is, what's important in that situation, and how it maps onto physical principles and equations. If students don't understand that part of the process, they can have great difficulty in seeing the physics as a way to make sense of the physical world.[10]

[10] The Physics Education Group at the University of Massachusetts—Amherst has done interesting research using problem posing as a technique to help students develop these skills [Mestre 1991]. See also the variety of problems discussed in chapter 4.

A shepherd has 125 sheep and 5 dogs. How old is the shepherd?

Figure 3.1 A word problem for middle school math students.

A classic word problem that illustrates this difficulty is shown in Figure 3.1. Although this problem is patently absurd and cannot be answered, some middle school students will struggle to find an answer (Expectation: "The teacher wouldn't give me a problem that has no solution.") and will come up with an answer of 25. ("There are only two numbers to work with: 5 and 125. Adding, multiplying, and subtracting them doesn't give something that could be an age. Only dividing gives a plausible number.")

Another example comes from the mathematics exam given by the National Assessment of Educational Progress (NAEP). A national sample of 45,000 13-year-olds was given the problem shown in Figure 3.2 [Carpenter 1983]. Although 70% of the students who worked the problem carried out the long division correctly, only 23% gave the correct answer—32. The answer "31 remainder 12" was given by 29%, and the answer 31 was given by another 18% of those doing the problem. Thus, nearly half of the students who were able to carry out the formal manipulations correctly failed to perform the last simple step required by the problem: to think about what the answer meant in terms of a real-world situation. (Expectation: "The mathematical manipulation is what's important and what is being tested.")

In these two examples, students are making somewhat different errors. In the shepherd problem they *are* using some real-world information—what ages are plausible as answers; but they are not asking how the numbers they are given could relate to the answer. They are not making sense of the problem. In the soldiers and buses problem, students are *not* using their real-world knowledge that you cannot rent a fraction of a bus. In both cases, students who make these errors focus on the mathematical manipulations and fail to "make sense" of the problem in real-world terms.

The same problems occur frequently in introductory physics. In my experience with introductory college physics, more than half of the students do not spontaneously connect what they learn in their physics class to their everyday experiences—either by bringing their everyday experiences into their physics classes or by seeing the physics they are learning in the outside world. Two anecdotal examples show how this plays out in a college physics class.

A student in my algebra-based physics class missed a midsemester exam due to an illness, and I agreed to give her a makeup. One of the problems on the exam was the following. "A high jumper jumps so his center of gravity rises 4 feet before he falls back to the ground. With what speed did he leave the ground?" This is a typical projectile problem. My

An army bus holds 36 soldiers. If 1128 soldiers are being bused to their training site, how many buses are needed?

Figure 3.2 A problem for the NAEP math exam for middle school students.

student knew the formula and punched the numbers into her calculator. When she handed in her test and I looked over her answers, she had come up with the answer 7840 feet/second. (Can you guess what she had done wrong on her calculator?) I asked her whether her answer to that problem had bothered her. She shrugged and said, "That's what the formula gave me." She saw absolutely no need to check her answer against her experience—and incidentally, it had never entered her mind that she might have misremembered the formula, incorrectly recalled the value of a parameter, or made an error in pressing the calculator keys. This overconfidence in their memory and processing is a symptom I have seen in very many students. They assume anything they remember must be correct.

A second example occurred in my engineering (calculus-based) physics class. For many years now, I have been requiring estimation (Fermi-type) problems in my classes.[11] Almost every homework assignment has one, and every exam is guaranteed to have one. One of my students came into my office hours and complained that this wasn't fair. "I don't know how big these things are," she scowled. "Well," I said. "How about a foot? Do you know how big a foot is?" "I have no idea," she replied. Assuming that she was overstating her case to make her point, I said, "How about making a guess? Show me how far up from the floor a foot would be." She placed her hand at about waist level. "And how tall are you?" I asked. She thought for a second, said "Oh" and lowered her hand somewhat. She thought again and lowered her hand again—to about the right height above the ground. She looked at her hand—and at her foot a few inches away and remarked with great (and what appeared to be genuine) surprise, "Oh! Does it have anything to do with a person's foot?"

Since these real-world connections are critically important in developing an understanding of how physics helps us to make sense of our everyday experiences,[12] I specify a fourth learning goal.

> <u>*Goal 4*</u>: Reality Link—Our students should connect the physics they are learning with their experiences in the physical world.

To what extent does a traditional course help our students reach this goal? The simplest way to find out is to ask them.[13] In our study of student expectations in a calculus-based physics class for engineers [Redish 1998], using the MPEX survey[14] we found that student expectations of the connection between physics and the real world typically tended to deteriorate as a result of the first semester of instruction.

The four items of the MPEX reality cluster are shown in Table 3.2. They ask whether students expect to/have needed to[15] make the link to their outside experiences for the class and whether students expect to/have found that what they learn in physics can be seen in

[11] For examples of these types of problems, see chapter 4 and the sample problems on the Resource CD.

[12] This is especially true for our service students in engineering and biology.

[13] This method is not very accurate since students often do not reflect and do not necessarily know how they think. A better approach is to watch them solving problems alone or in a group using think-aloud protocols [Ericson 1993].

[14] See chapter 5 for a detailed discussion of the MPEX. The full survey and instructions on its use are contained in the Action Research Kit on the Resource CD.

[15] The alternate forms are for the pre- and post-class surveys.

TABLE 3.2 Results on the MPEX Reality Link Cluster Items

MPEX Item	Favorable Pre	Unfavorable Pre	Favorable Post	Unfavorable Post
Physical laws have little relation to what I experience in the real world. (−)	84%	5%	87%	2%
To understand physics, I sometimes think about my personal experiences and relate them to the topic being analyzed. (+)	59%	11%	54%	22%
Physics is related to the real world, and it sometimes helps to think about the connection, but it is rarely essential for what I have to do in this course. (−)	73%	9%	61%	19%
Learning physics helps me understand situations in my everyday life. (+)	72%	10%	51%	18%

their real-world experiences. Both issues are addressed in two statements, one positive and one negative. The student's response is considered to be *favorable* if she sees the need for a connection and *unfavorable* if she does not. The polarity of the favorable result is indicated after the item by a (+) when the favorable result is *agree* and by a (−) when the favorable result is *disagree*. The students are asked to report on a five-point scale (strongly agree, agree, neutral, disagree, strongly disagree), but for a favorable/unfavorable analysis, we ignore whether or not there is a "strongly." The responses come from pre- and post-surveys given in the first semester of an engineering physics class. The class was calculus-based and covered mostly Newtonian mechanics. The results are shown for $N = 111$ students (matched, i.e., who completed both pre- and post-surveys).[16]

The results are discouraging, especially on the last two items. I tried to help my students make the connection by giving some estimation problems, but that was clearly insufficient. Similar results have been found with other faculty teaching this class at Maryland and at many other colleges and universities [Redish 1998].

There has been little published work on how to help students develop a strong reality link. In my experience, regular essay questions asking the students to relate the physics to their experience and regular estimation questions (being sure to include both on every exam so that students take them seriously) only help a little bit. Even in lessons where physicists see real-world implications immediately, students rarely make the connections spontaneously

[16] A total of 158 students completed the class.

if not led to them. I expect this goal will only be achieved by a thorough interweaving of the physics with explicit connections to the students' experience.[17] Further research and development on this issue would be most welcome.

METACOGNITION: THINKING ABOUT THINKING

The transcript from David Hammer's high school class in our earlier discussion shows that different students access different kinds of reasoning in their discussion of a physics problem. This variety arises from students having different expectations about the nature of science and what it means to learn science. Unfortunately, many of these expectations are inappropriate for learning science. They may be learned in school, from movies and TV, or from reading science fiction books.[18] When students have the wrong expectations about what they are supposed to do in a class, those expectations can serve as a filter, causing them to ignore even explicit instructions given by the instructor.

In part, the approaches to learning physics that students bring into our classes arise from a misunderstanding of the nature of scientific knowledge and how one has to learn it. As pointed out so clearly by diSessa and discussed in chapter 2, for most ordinary people (even for some of our best students[19]) knowledge of the world comes in "pieces" about how particular situations work [diSessa 1993] [diSessa 1988]. As pointed out by Reif and Larkin [Reif 1991], building a consistent and economical set of principles—at the cost of requiring long and indirect explanations of many phenomena—is not the way most people create their models of the physical world in their everyday lives. It seems that people tend to look for quick and direct explanations. The complex consistent and parsimonious net of links built by science is not a natural type of mental construction for most people. It has to be learned.

The key element in the mental model I want my students to use in learning physics appears to me to be *reflection*—thinking about their own thinking. This includes a variety of activities, including evaluating their ideas, checking them against experience, thinking about consistency, deciding what's fundamental that they need to keep and what is peripheral and easily reconstructed, considering what other ideas might be possible, and so on. My experience with students in introductory classes—even advanced students[20]—is that they rarely expect to think about their knowledge in these ways. Students often come to my office hours for help with problems. I always ask them to show me what they have tried so far and proceed to offer help via questions. They frequently have an error close to the start of their analysis—in a principle or equation that they bring up from their memory. As I lead them to implausible and unlikely results through my questioning they become troubled, but they are much more likely to try to justify a ridiculous result by difficult and inconvenient contorted reasoning than by asking if one of their assumptions might be wrong.

[17] Preliminary results with a more synergistic approach appear quite favorable [Redish 2001].

[18] Some science fiction books, especially those written by scientists (such as David Brin, Gregory Benford, or John Kramer), have excellent descriptions of the way science develops its knowledge.

[19] Recall that in [diSessa 1993] the subjects studied were MIT freshmen.

[20] Many of the students in my algebra-based physics classes are upper division students who have previously taken many science classes in chemistry and biology.

From our cognitive model we understand that to create new, coherent, and well-structured mental models, students need to go through a number of well-designed activities addressing the issue to be learned, to repeat them, and to reflect on them. Similar principles hold for metacognition—thinking that reflects on the thinking process itself. I add another learning goal to the list developed in chapter 2.

> *Goal 5*: Metalearning—Our students should develop a good understanding of what it means to learn science and what they need to do to learn it. In particular, they need to learn to evaluate and structure their knowledge.

This is not a trivial goal and it does not happen automatically for most students as they work to learn physics content.

> *Redish's second teaching commandment:* In order for most students to learn how to learn and think about physics, they have to be provided with explicit instruction that allows them to explore and develop more sophisticated schemas for learning.

"Hold on!" Sagredo complains. "I never have time enough to teach all the content I'm supposed to teach. How can I find time to give them lessons in how to learn?" I sympathize, Sagredo. But in fact, the problem is not as bad as it looks. If we are teaching them to learn, we have to be teaching them to learn *something*. That something can easily be the appropriate physics content. Some introductory discussion, lessons designed to encourage particular activities, and reflections analyzing what they've done should help substantially. One of the few well-documented approaches to explicitly teaching and improving students' metacognition is the work of Alan Schoenfeld.

Instructional techniques for improving metacognition

Alan Schoenfeld, in a problem-solving college math class, developed a group-problem-solving method that focused on helping students strengthen their judgment and control of their own thinking. The class was small enough (on the order or fewer than 25 students) that he could use a guided cooperative group-problem-solving approach.[21]

In his observations of the class's behavior, Schoenfeld found that his students often wasted a lot of time in following unproductive approaches through a lack of metacognitive activity. The students quickly jumped on the first idea that came to their minds and then proceeded to "churn" through extensive manipulations, frequently losing track of what they were doing and rarely evaluating whether their approach was productive.

Schoenfeld developed an instructional method to help students become more metacognitively aware. The key was the mantra of metacognitive questions posted on the wall shown in Figure 3.3. His comments on how this worked are worth repeating.

> Students' decision-making processes are usually covert and receive little attention. When students fail to solve a problem, it may be hard to convince them that their failures may be due to bad

[21] See chapter 8 for a discussion of a method of this type employed in physics to help develop students' conceptual development and problem-solving skills.

What (exactly) are you doing?
(Can you describe it precisely?)
Why are you doing it?
(How does it fit into the solution?)
How does it help you?
(What will you do with the outcome when you get it?)

Figure 3.3 Schoenfeld's questions for helping students learn to focus on metacognitive issues.

decision-making rather than to a lack of knowledge. The instructor had the right to stop students at any time while they were working on the problems and to ask them to answer the three questions on [Figure 3.4]. At the beginning of the course the students were unable to answer the questions, and they were embarrassed by that fact. They began to discuss the questions in order to protect themselves against further embarrassment. By the middle of the term, asking the questions of themselves (not formally, of course) had become habitual behavior for some of the students. [Schoenfeld 1985]

Schoenfeld not only implemented a focus on metacognition and control in the group activity, but he modeled it in his approach to modeling solutions for the class as a whole. His description outlines the process in detail.

When the class convened as a whole to work problems (40–50% of class time), I served as orchestrator of the students' suggestions. My role was not to lead the students to a predetermined solution, . . . my task was to role model competent control behavior—to raise the questions and model the decision-making processes that would help them to make the most of what they know. Discussions started with "What do you think we should do?" to which some student usually

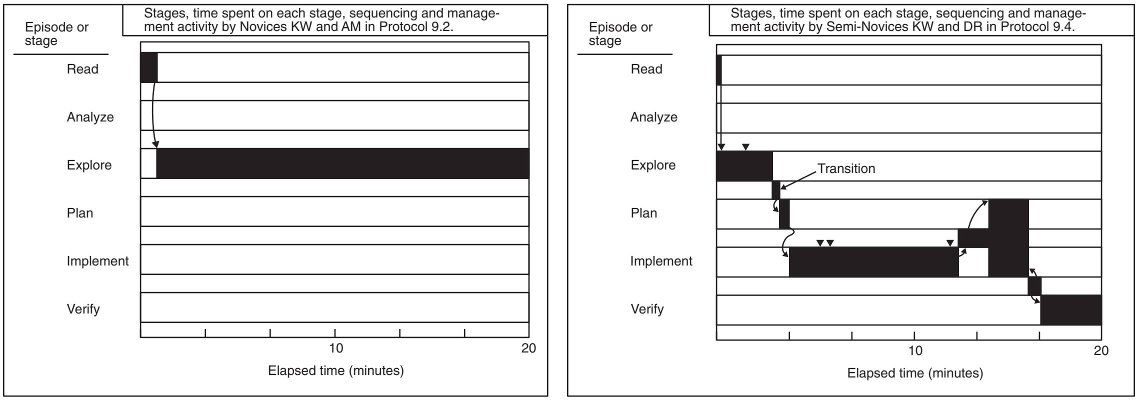

Figure 3.4 Sample plots of student activities in solving math problems in Alan Schoenfeld's metacognitive math class. Small triangles mark metacognitive statements [Schoenfeld 1985].

> suggested "Let's do X." Often the suggestion came too rapidly, indicating that the student had not adequately thought through what the problem called for or how the suggestion might be useful. The class was then asked, "Are you all sure you understand the problem, before we proceed with X?" A negative response from some students would result in our taking a closer look at the problem. After doing so, we returned to X as a possible solution approach. Did X still seem reasonable? Not infrequently the answer was "no." When it was, this provided the opportunity to remind students about the importance of making sure that one has understood a problem before jumping into its solution. . . . After a few minutes of working on the problem—whether or not we were on a track that would lead to a solution—the process would be halted for an assessment of how things were going. The class was asked "We've been doing this for 5 minutes. Is it useful, or should we switch to something else? (and why?)" Depending on the evaluation, we might or might not decide to continue in that direction: we might decide to give it a few more minutes before trying something else. Once we had arrived at a solution, I did a postmortem on the solution. The purpose of that discussion was to summarize what the class had done and to point out where it could have done something more efficiently, or perhaps to show how an idea that the class had given up on could have been exploited to solve the problems. . . . The same problem was often solved three or four different ways before we were done with it. [Schoenfeld 1985]

By the end of the class, Schoenfeld found that the students were spending a much larger fraction of their time in planning and evaluation and that their "metacognitive events" (statements like: "I don't understand this" or "That doesn't seem right") more often led to their jumping into planning or checking mode than it did at the beginning of the class. This is illustrated in Figure 3.4.

AFFECT: MOTIVATION, SELF-IMAGE, AND EMOTION

It is patently clear to most university physics instructors that motivation, how students feel about the class, and how the students feel about themselves, play a critical role in how students respond to instruction and how well they learn. The issues of feeling, emotion, and mood are summarized by the term *affect* or *affection* in psychology. These issues have been discussed extensively in the educational literature, [Graham 1996] [Stipek 1996], but I do not attempt to review this literature here as the interaction between affect and cognition is extremely complex and it is difficult to provide precise guidance. This is not to say these issues are not of great importance. I therefore make a few comments, but refer the reader to the literature cited above for details.

Motivation

Motivation can be a major factor in distinguishing students who will make the effort to learn and those who will not. We encounter a variety of motivations.

- *Internally motivated*—Some students who come to our classes are self-motivated by an interest in physics and a desire for learning.
- *Externally motivated*—Some students have no internal interest in physics but are strongly motivated to get a good grade because our class is a hoop that must be jumped through for them to get into a program for which they are motivated.

- *Weakly motivated*—These students are taking physics because it is a requirement, but they are concerned only about passing, not getting a good grade.
- *Negatively motivated*—Some students are motivated to fail—for example, in order to demonstrate to a controlling parent or mentor that they are not suited to be an engineer or a doctor.

Those in the first group are a physics instructor's delight. Whatever you give them they make the most of. We can work with those in the second group by controlling the learning environments we set up and making clear what will be evaluated on exams. (See examples in chapter 4.) I can rarely do anything with the last group. Their goals in the class are distinctly different from mine.

Finding ways to motivate your students to want to learn physics can be an extremely effective lever to improve the success of your teaching. Unfortunately, this is easier said than done and is where much of the "art" in teaching comes in. It is easy to mistake student happiness for student motivation. Making your lecture "entertaining" does not necessarily increase students' motivation for learning. Indeed, it can set up the expectation in their minds that associates your lecture with a TV program where they don't have to think.

Providing connections to their chosen career sometimes helps. I evolve my estimation problems into design problems in my engineering physics class and create problems with a medical and biological context for my algebra-based students. I hope this helps them see the relevance of physics to a profession toward which they should, in principle, be motivated. (Interviews with a small number of volunteers—usually the better students—suggest that at least this group is making the connection [Lippmann 2001].)

Motivation is perhaps the primary place where the teacher in fact makes a significant difference. A teacher with the empathy and charisma to motivate the students can create substantially more intellectual engagement than one who reads from the book and does not take the time to interact with the students. Perhaps the most critical element in creating motivation is showing your students that you are interested in them, you want them to succeed, and you believe that they can do it.

Self-image

Sagredo is a bit skeptical about the issue of students' self-image. He feels that the education community pushes "helping students feel good about themselves," sometimes to the detriment of serious critical self-analysis and learning, at least if the letters to the editor published in newspapers are to be believed. In my experience with university-level physics students, this issue cuts two ways. Some students are supremely overconfident, while others think that they cannot possibly understand physics. Both groups are difficult to deal with.

In our small-group-sessions, we often use the Tutorial materials developed at the University of Washington. These lessons are research-based group-learning worksheets (see chapter 8 for a detailed description) and use a cognitive conflict model. As a result, students who are used to being right often feel the Tutorials are trivial and therefore useless—even when they are consistently getting the wrong answers. When I am facilitating in one of these sessions, I see this as a terrific learning opportunity. I circulate through the class, asking what they got on the tricky questions. When I find a group that has been overwhelmed by an overconfident student with a wrong answer, I say, "Now remember: Physics is not a democracy and physics is not determined by charisma. You can't tell who's right by who says it the most

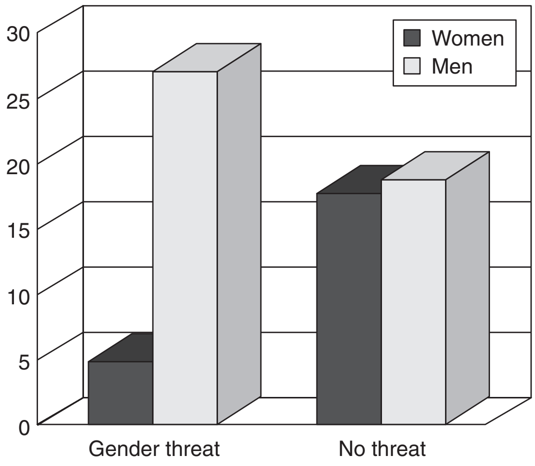

Figure 3.5 Scores of college sophomore males and females on a math test when a comment is made that the test "tends to separate genders" and when no such comment is made [Steele 1997].

forcefully or by what most people think. It has to make sense and it has to be consistent. Perhaps you want to go back and think that question out again." The result is almost always that someone else in the group who had previously been intimidated into silence can bring everyone to the correct result. This sends a really useful message—both for the overconfident student and for the other members of the group.

On the other side, I have had experience with students who were absolutely convinced that they were incapable of learning physics. In one case, I had a student in algebra-based physics who was convinced "she couldn't do this stuff" and told me so repeatedly. However, I often watched her vigorously argue difficult issues in Tutorials with another student who was supremely confident of her ability and answers. My underconfident student was almost always right, and my overconfident student almost always wrong.

Despite her success in Tutorials, this student did not change her overall self-evaluation of her ability and she did poorly on exams. In other cases, I was able to help students who were good in other classes but who, perhaps because of bad experiences in high school, were convinced that they "couldn't do physics." All these cases are best treated carefully and individually, using all the empathy and understanding you can bring to bear. Unfortunately, in many college and university situations, the pressure of time and numbers makes it difficult, if not impossible, to allow you to offer the individualized responses needed.

There has been some research on the topic of math anxiety or "math phobia." (See, for example, [Tobias 1995].) I do not know of comparable work on "science phobia." There has also been some extremely important work on the implications of social stereotypes on self-image and performance. Stanford sociologist Claude Steele explored the implications of raising the link in a student's mind to gender or race in conjunction with a mathematics test [Steele 1997]. College sophomores who had committed themselves to a math major or minor were given a test somewhat above their level. One group was told that the test was "just a trial" and that the researchers "wanted to see how they would do." A second group was told up front that the test "showed gender differences." (The sign of the difference was not specified.) The results, shown in Figure 3.5, were dramatic. In the group given the test without any comment about gender, males and females scored approximately the same. In the group with the comment about gender, referred to as a *gender threat* by Steele,[22] females scored significantly worse (by more than a factor of 3!), and males scored somewhat better (about 50%).

The implication appears to be that stereotypes (males are better in math) pervade our culture in a profound way, with implications that we tend to be unaware of and are insensitive to. This certainly suggests that we should be extremely cautious about making *any* comments at all about gender or race to our classes. For researchers, it suggests that in doing interviews or surveys, questions about the respondent's gender, race, or other social factors should be given separately after the testing is complete.

Emotion

"I'm a physicist, not a song-and-dance-man!" Sagredo complains, echoing Star Trek's Dr. McCoy. Perhaps, Sagredo, but making your students feel good about your class can have an influence on their learning. For one, if they hate your lectures and don't come to class, they won't be able to learn anything from them.[23] On the other hand, if you fill your lecture with jokes, films, and cartoons, they are unlikely to take them seriously.

The best thing you can do to make students "feel good" about your class is to make it worthwhile, at an appropriate level, and fair. Students like to feel that they are learning something valuable and that they can get a "good" grade (this may have different meanings for different students) without having to work so hard that their other classes (and their social lives) suffer. Getting students to learn a lot from our classes is a process of negotiation. From my point of view as a teacher, I want them to work hard, but from their point of view as a student, they don't want to work hard without a clear payoff. In physics, learning can be frustrating and nonlinear. Often you have to work for a long time without feeling that you are making much progress. Then, suddenly, everything falls into place and it all makes sense. But until the "click," you can't be sure how much time you need to "get it" and it's difficult to plan. Students first have to learn what understanding the physics feels like and be slowly drawn into working hard enough to learn harder and harder topics.

But entertainment and "song-and-dance" don't have to be shunned, Sagredo. In our context, it can mean little physics jokes, personalized stories, and dramatic demonstrations. (But see the discussion of demonstrations in chapter 7.) All of these can be effective—or not. Jokes should be relevant, not off-color, and not derogatory to groups or individuals. Personalized stories should be relevant to the physics involved and have some point that will make sense to a novice. They shouldn't occupy so much of the time that students begin to feel you're not offering them enough physics. Demonstrations can be the best but are also dangerous. As explained in chapter 7, demonstrations can be entertaining but misleading. Students often don't see what you think they are seeing. A careful and involving class discussion, both before and after the demonstration, is usually needed.

[22] Note that the "threat" is implicit. There was no statement as to which group was expected to do better, and there were no consequences for the students no matter how they scored.

[23] Students tend to learn little even from lectures they attend unless special tools are used. See chapter 7.