



A FINAL SYNTHESIS: REVISITING THE THREE LEARNING PRINCIPLES

13

Pulling Threads

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What ties the chapters of this volume together are the three principles from *How People Learn* (set forth in Chapter 1) that each chapter takes as its point of departure. The collection of chapters in a sense serves as a demonstration of the second principle: that a solid foundation of detailed knowledge and clarity about the core concepts around which that knowledge is organized are both required to support effective learning. The three principles themselves are the core organizing concepts, and the chapter discussions that place them in information-rich contexts give those concepts greater meaning. After visiting multiple topics in history, math, and science, we are now poised to use those discussions to explore further the three principles of learning.

ENGAGING RESILIENT PRECONCEPTIONS

All of the chapters in this volume address common preconceptions that students bring to the topic of focus. Principle one from *How People Learn* suggests that those preconceptions must be engaged in the learning process, and the chapters suggest strategies for doing so. Those strategies can be grouped into three approaches that are likely to be applicable across a broad range of topics.

1. *Draw on knowledge and experiences that students commonly bring to the classroom but are generally not activated with regard to the topic of study.*

This technique is employed by Lee, for example, in dealing with students' common conception that historical change happens as an *event*. He points out that students bring to history class the everyday experience of "nothing much happening" until an event changes things. Historians, on the other hand, generally think of change in terms of the *state of affairs*. Change in this sense may include, but is not equivalent to, the occurrence of events. Yet students have many experiences in which things change gradually—experiences in which "nothing happening" is, upon reflection, a mischaracterization. Lee suggests, as an example, students might be asked to "consider the change from a state of affairs in which a class does not trust a teacher to one in which it does. There may be no event that could be singled out as marking the change, just a long and gradual process."

There are many such experiences on which a teacher could draw, such as shifting alliances among friends or a gradual change in a sports team's status with an improvement in performance. Each of these experiences has characteristics that support the desired conception of history. Events are certainly not irrelevant. A teacher may do particular things that encourage trust, such as going to bat for a student who is in a difficult situation or postponing a quiz because students have two other tests on the same day. Similarly, there may be an incident in a group that changes the dynamic, such as a less popular member winning a valued prize or taking the blame for an incident to prevent the whole group from being punished. But in these contexts students can see, perhaps with some guided discussion, that single events are rarely the sole explanation for the state of affairs.

It is often the case that students have experiences that can support the conceptions we intend to teach, but instructional guidance is required to bring these experiences to the fore. These might be thought of as "recessive" experiences. In learning about rational number, for example, it is clear that whole-number reasoning—the subject of study in earlier grades—is dominant for most students (see Chapter 7). Yet students typically have experience with thinking about percents in the context of sale items in stores, grades in school, or loading of programs on a computer. Moss's approach to teaching rational number as described in Chapter 7 uses that knowledge of percents to which most students have easy access as an alternative path to learning rational number. She brings students' recessive understanding of proportion in the context of reasoning about percents to the fore and strengthens their knowledge and skill by creating multiple contexts in which proportional reasoning is employed (pipes and tubes, beakers, strings). As with events in history, students do later work with fractions, and that work at times presents them with problems that involve dividing a pizza or a pie into discrete parts—a problem in which whole-number reasoning often dominates. Because a facility with proportional reasoning is brought to bear,

however, the division of a pie no longer leads students so easily into whole-number traps.

Moss reinforces proportional reasoning by having students play games in which fractions (such as $\frac{1}{4}$) must be lined up in order of size with decimals (such as .33) and percents (such as 40 percent). A theme that runs throughout the chapters of this volume, in fact, is that students need many opportunities to work with a new or recessive concept, especially when doing so requires that powerful preconceptions be overturned or modified.

Bain, for example, writes about students' tendency to see "history" and "the past" as the same thing: "No one should think that merely pointing out conceptual distinctions through a classroom activity equips students to make consistent, regular, and independent use of these distinctions. Students' habits of seeing history and the past as the same do not disappear overnight." Bain's equivalent of repeated comparisons of fractions, decimals, and percents is the ever-present question regarding descriptions and materials: is this "history-as-event"—the description of a past occurrence—or "history-as-account"—an explanation of a past occurrence. Supporting conceptual change in students requires repeated efforts to strengthen the new conception so that it becomes dominant.

2. Provide opportunities for students to experience discrepant events that allow them to come to terms with the shortcomings in their everyday models.

Relying on students' existing knowledge and experiences can be difficult in some instances because everyday experiences provide little if any opportunity to become familiar with the phenomenon of interest. This is often true in science, for example, where the subject of study may require specialized tools or controlled environmental conditions that students do not commonly encounter.

In the study of gravity, for example, students do not come to the classroom with experiences that easily support conceptual change because gravity is a constant in their world. Moreover, experiences they have with other forces often support misconceptions about gravity. For example, students can experience variation in friction because most have opportunities to walk or run an object over such surfaces as ice, polished wood, carpeting, and gravel. Likewise, movement in water or heavy winds provide experiences with resistance that many students can easily access. Minstrell found his students believed that these forces with which they had experience explained why they did not float off into space (see Chapter 11). Ideas about buoyancy and air pressure, generally not covered in units on gravity, influenced these students' thinking about gravity. Television images of astronauts floating in space reinforced for the students the idea that, without air to hold things down, they would simply float off.

Minstrell posed to his students a question that would draw out their thinking. He showed them a large frame from which a spring scale hung and placed an object on the scale that weighed 10 pounds. He then asked the students to consider a situation in which a large glass dome would be placed over the scale and all the air forced out with a vacuum pump. He asked the students to predict (imprecisely) what would happen to the scale reading. Half of Minstrell's students predicted that the scale reading would drop to zero without air; about a third thought there would be no effect at all on the scale reading; and the remainder thought there would be a small change. That students made a prediction and the predictions differed stimulated engagement. When the experiment was carried out, the ideas of many students were directly challenged by the results they observed.

In teaching evolution, Stewart and colleagues found that students' everyday observations led them to underestimate the amount of variation in common species. In such cases, student observations are not so much "wrong" as they are insufficiently refined. Scientists are more aware of variation because they engage in careful measurement and attend to differences at a level of detail not commonly noticed by the lay person. Stewart and colleagues had students count and sort sunflower seeds by their number of stripes as an easy route to a discrepant event of sorts. The students discovered there is far more variation among seeds than they had noticed. Unless students understand this point, it will be difficult for them to grasp that natural selection working on natural variation can support evolutionary change.

While discrepant events are perhaps used most commonly in science, Bain suggests they can be used productively in history as well (see Chapter 4). To dislodge the common belief that history is simply factual accounts of events, Bain asked students to predict how people living in the colonies (and later in the United States) would have marked the anniversary of Columbus's voyage 100 years after his landing in 1492 and then each hundred years after that through 1992. Students wrote their predictions in journals and were then given historical information about the changing Columbian story over the 500-year period. That information suggests that the first two anniversaries were not really marked at all, that the view of Columbus's "discovery of the new world" as important had emerged by 1792 among former colonists and new citizens of the United States, and that by 1992 the Smithsonian museum was making no mention of "discovery" but referred to its exhibit as the "Columbian Exchange." If students regard history as the reporting of facts, the question posed by Bain will lead them to think about *how* people might have celebrated Columbus's important discovery, and not *whether* people would have considered the voyage a cause for celebration at all. The discrepancy between students' expectation regarding the answer to the question and the historical accounts they are given in the classroom

lecture cannot help but jar the conception that history books simply report events as they occurred in the past.

3. Provide students with narrative accounts of the discovery of (targeted) knowledge or the development of (targeted) tools.

What we teach in schools draws on our cultural heritage—a heritage of scientific discovery, mathematical invention, and historical reconstruction. Narrative accounts of how this work was done provide a window into change that can serve as a ready source of support for students who are being asked to undergo that very change themselves. How is it that the earth was discovered to be round when nothing we casually observe tells us that it is? What is place value anyway? Is it, like the round earth, a natural phenomenon that was discovered? Is it truth, like $e = mc^2$, to be unlocked? There was a time, of course, when everyday notions prevailed, or everyday problems required a solution. If students can witness major changes through narrative, they will be provided an opportunity to undergo conceptual change as well.

Stewart and colleagues describe the use of such an approach in teaching about evolution (see Chapter 12). Darwin's theory of natural selection operating on random variation can be difficult for students to grasp. The beliefs that all change represents an advance toward greater complexity and sophistication and that changes happen in response to use (the giraffe's neck stretching because it reaches for high leaves, for example) are widespread and resilient. And the scientific theory of evolution is challenged today, as it was in Darwin's time, by those who believe in intelligent design—that all organisms were made perfectly for their function by an intelligent creator. To allow students to differentiate among these views and understand why Darwin's theory is the one that is accepted scientifically, students work with three opposing theories as they were developed, supported, and argued in Darwin's day: William Paley's model of intelligent design, Jean Baptiste de Lamarck's model of acquired characteristics based on use, and Darwin's theory of natural selection. Students' own preconceptions are generally represented somewhere in the three theories. By considering in some depth the arguments made for each theory, the evidence that each theorist relied upon to support his argument, and finally the course of events that led to the scientific community's eventually embracing Darwin's theory, students have an opportunity to see their own ideas argued, challenged, and subjected to tests of evidence.

Every scientific theory has a history that can be used to the same end. And every scientific theory was formulated by particular people in particular circumstances. These people had hopes, fears, and passions that drove their work. Sometimes students can understand theories more readily if they learn about them in the context of those hopes, fears, and passions. A narrative

that places theory in its human context need not sacrifice any of the technical material to be learned, but can make that material more engaging and meaningful for students.

The principle, of course, does not apply only to science and is not restricted to discovery. In mathematics, for example, while some patterns and relationships were discovered, conventions that form our system of counting were *invented*. As the mathematics chapters suggest, the use of mathematics with understanding—the engagement with problem solving and strategy use displayed by the best mathematics students—is undermined when students think of math as a rigid application of given algorithms to problems and look for surface hints as to which algorithm applies. If students can see the nature of the problems that mathematical conventions were designed to solve, their conceptions of what mathematics is can be influenced productively.

Historical accounts of the development of mathematical conventions may not always be available. For purposes of supporting conceptual change, however, fictional story telling may do just as well as history. In *Teaching as Story Telling*, Egan¹ relates a tale that can support students' understanding of place value:

A king wanted to count his army. He had five clueless counselors and one ingenious counselor. Each of the clueless five tried to work out a way of counting the soldiers, but came up with methods that were hopeless. One, for example, tried using tally sticks to make a count, but the soldiers kept moving around, and the count was confused. The ingenious counselor told the king to have the clueless counselors pick up ten pebbles each. He then had them stand behind a table that was set up where the army was to march past. In front of each clueless counselor a bowl was placed. The army then began to march past the end of the table.

As each soldier went by, the first counselor put one pebble into his bowl. Once he had put all ten pebbles into the bowl, he scooped them up and then continued to put one pebble down for each soldier marching by the table. He had a very busy afternoon, putting down his pebbles one by one and then scooping them up when all were in the bowl. Each time he scooped up the ten pebbles, the clueless counselor to his left put one pebble into her bowl [gender equity]. When her ten pebbles were in her bowl, she too scooped them out again, and continued to put one back into the bowl each time the clueless counselor to her right picked his up.

The clueless counselor to her left had to watch her through the afternoon, and he put one pebble into his bowl each time she picked

bers up. And so on for the remaining counselors. At the end of the afternoon, the counselor on the far left had only one pebble in his bowl, the next counselor had two, the next had seven, the next had six and the counselor at the other end of the table, where the soldiers had marched by, had three pebbles in his bowl. So we know that the army had 12,763 soldiers. The king was delighted that his ingenious counselor had counted the whole army with just fifty pebbles.²

When this story is used in elementary school classrooms, Egan encourages the teacher to follow up by having the students count the class or some other, more numerous objects using this method.

The story illustrates nicely for students how the place-value system allows the complex problem of counting large numbers to be made simpler. Place value is portrayed not as a truth but as an invention. Students can then change the base from 10 to other numbers to appreciate that base 10 is not a “truth” but a “choice.” This activity supports students in understanding that what they are learning is designed to make number problems raised in the course of human activity manageable.

That imaginative stories can, if effectively designed, support conceptual change as well as historical accounts is worth noting for another reason: the fact that an historical account is an *account* might be viewed as cause for excluding it from a curriculum in which the nature of the account is not the subject of study. Historical accounts of Galileo, Newton, or Darwin written for elementary and secondary students can be contested. One would hope that students who study history will come to understand these as accounts, and that they will be presented to students as such. But the purpose of the accounts, in this case, is to allow students to experience a time when ideas that they themselves may hold were challenged and changed, and that purpose can be served even if the accounts are somewhat simplified and their contested aspects not treated fully.

ORGANIZING KNOWLEDGE AROUND CORE CONCEPTS

In the *Fish Is Fish* story discussed in Chapter 1, we understand quite easily that when the description of a human generates an image of an upright fish wearing clothing, there are some key missing concepts: adaptation, warm-blooded versus cold-blooded species, and the difference in mobility challenges in and out of water. How do we know which concepts are “core?” Is it always obvious?

The work of the chapter authors, as well as the committee/author discussions that supported the volume’s development, provides numerous in-

sights about the identification of core concepts. The first is observed most explicitly in the work of Peter Lee (see Chapter 2): that two distinct types of core concepts must be brought to the fore simultaneously. These are concepts about the nature of the discipline (what it means to engage in doing history, math, or science) and concepts that are central to the understanding of the subject matter (exploration of the new world, mathematical functions, or gravity). Lee refers to these as first-order (the discipline) and second-order (the subject) concepts. And he demonstrates very persuasively in his work that students bring preconceptions about the discipline that are just as powerful and difficult to change as those they bring about the specific subject matter.

For teachers, knowing the core concepts of the discipline itself—the standards of evidence, what constitutes proof and disproof, and modes of reasoning and engaging in inquiry—is clearly required. This requirement is undoubtedly at the root of arguments in support of teachers' course work in the discipline in which they will teach. But that course work will be a blunt instrument if it focuses only on second-order knowledge (of subject) but not on first-order knowledge (of the discipline). Clarity about the core concepts of the discipline is required if students are to grasp what the discipline—history, math, or science—is about.

For identifying both first- and second-order concepts, the obvious place to turn initially is to those with deep expertise in the discipline. The concepts that organize experts' knowledge, structure what they see, and guide their problem solving are clearly core. But in many cases, exploring expert knowledge directly will not be sufficient. Often experts have such facility with a concept that it does not even enter their consciousness. These "expert blind spots" require that "knowledge packages"³—sets of related concepts and skills that support expert knowledge—become a matter for study.

A striking example can be found in Chapter 7 on elementary mathematics. For those with expertise in mathematics, there may appear to be no "core concept" in whole-number counting because it is done so automatically. How one first masters that ability may not be accessible to those who did so long ago. Building on the work of numerous researchers on how children come to acquire whole-number knowledge, Griffin and Case's⁴ research conducted over many years suggests a core conceptual structure that supports the development of the critical concept of *quantity*. Similar work has been done by Moss and Case⁵ (on the core conceptual structure for rational number) and by Kalchman, Moss, and Case⁶ (on the core conceptual structure for functions). The work of Case and his colleagues suggests the important role cognitive and developmental psychologists can play in extending understanding of the network of concepts that are "core" and might be framed in less detail by mathematicians (and other disciplinary experts).

The work of Stewart and his colleagues described in Chapter 12 is another case in which observations of student efforts to learn help reshape understanding of the package of related core concepts. The critical role of natural selection in understanding evolution would certainly be identified as a core concept by any expert in biology. But in the course of teaching about natural selection, these researchers' realization that students underestimated the variation in populations led them to recognize the importance of this concept that they had not previously identified as core. Again, experts in evolutionary biology may not identify population variation as an important concept because they understand and use the concept routinely—perhaps without conscious attention to it. Knowledge gleaned from classroom teaching, then, can be critical in defining the connected concepts that help support core understandings.

But just as concepts defined by disciplinary experts can be incomplete without the study of student thinking and learning, so, too, the concepts as defined by teachers can fall short if the mastery of disciplinary concepts is shallow. Liping Ma's study of teachers' understanding of the mathematics of subtraction with regrouping provides a compelling example. Some teachers had little conceptual understanding, emphasizing procedure only. But as Box 13-1 suggests, others attempted to provide conceptual understanding without adequate mastery of the core concepts themselves. Ma's work provides many examples (in the teaching of multidigit multiplication, division of fractions, and calculation of perimeter and area) in which efforts to teach for understanding without a solid grasp of disciplinary concepts falls short.

SUPPORTING METACOGNITION

A prominent feature of all of the chapters in this volume is the extent to which the teaching described emphasizes the development of metacognitive skills in students. Strengthening metacognitive skills, as discussed in Chapter 1, improves the performance of all students, but has a particularly large impact on students who are lower-achieving.⁷

Perhaps the most striking consistency in pedagogical approach across the chapters is the ample use of classroom discussion. At times students discuss in small groups and at times as a whole class; at times the teacher leads the discussion; and at times the students take responsibility for questioning. A primary goal of classroom discussion is that by observing and engaging in questioning, students become better at monitoring and questioning their own thinking.

In Chapter 5 by Fuson, Kalchman, and Bransford, for example, students solve problems on the board and then discuss alternative approaches to solving the same problem. The classroom dialogue, reproduced in Box 13-2, supports the kind of careful thinking about why a particular problem-solv-

BOX 13-1 Conceptual Explanation Without Conceptual Understanding

Liping Ma explored approaches to teaching subtraction with regrouping (problems like $52 - 25$, in which subtraction of the 5 ones from the 2 ones requires that the number be regrouped). She found that some teachers took a very procedural approach that emphasized the order of the steps, while others emphasized the concept of composing a number (in this case into 5 tens and 2 ones) and decomposing a number (into 4 tens and 12 ones). Between these two approaches, however, were those of teachers whose intentions were to go beyond procedural teaching, but who did not themselves fully grasp the concepts at issue. Ma⁸ describes one such teacher as follows:

Tr. Barry, another experienced teacher in the procedurally directed group, mentioned using manipulatives to get across the idea that “you need to borrow something.” He said he would bring in quarters and let students change a quarter into two dimes and one nickel: “a good idea might be coins, using money because kids like money. . . . The idea of taking a quarter even, and changing it to two dimes and a nickel so you can borrow a dime, getting across that idea that you need to borrow something.”

There are two difficulties with this idea. First of all, the mathematical problem in Tr. Barry’s representation was $25 - 10$, which is not a subtraction with regrouping. Second, Tr. Barry confused borrowing in everyday life—borrowing a dime from a person who has a quarter—with the “borrowing” process in subtraction with regrouping—to regroup the minuend by rearranging within place values. In fact, Tr. Barry’s manipulative would not convey any conceptual understanding of the mathematical topic he was supposed to teach.

Another teacher who grasps the core concept comments on the idea of “borrowing” as follows:⁹

Some of my students may have learned from their parents that you “borrow one unit from the tens and regard it as 10 ones”. . . . I will explain to them that we are not borrowing a 10, but decomposing a 10. “Borrowing” can’t explain why you can take a 10 to the ones place. But “decomposing” can. When you say decomposing, it implies that the digits in higher places are actually composed of those at lower places. They are exchangeable . . . borrowing one unit and turning it into 10 sounds arbitrary. My students may ask me how can we borrow from the tens? If we borrow something, we should return it later on.

ing strategy does or does not work, as well as the relative benefits of different strategies, that can support skilled mathematics performance.

Similarly, in the science chapters students typically work in groups, and the groups question each other and explain their reasoning. Box 13-3 reproduces a dialogue at the high school level that is a more sophisticated version of that among young mathematics students just described. One group of students explains to another not only what they concluded about the evolutionary purpose of different coloration, but also the thinking that led them to that conclusion and the background knowledge from an earlier example that supported their thinking. The practice of bringing other knowledge to bear in the reasoning process is at the heart of effective problem solving, but can be difficult to teach directly. It involves a search through one's mental files for what is relevant. If teachers simply give students the knowledge to incorporate, the practice and skill development of doing one's own mental search is shortchanged. Group work and discussions encourage students to engage actively in the mental search; they also provide examples from other students' thinking of different searches and search results. The monitoring of consistency between explanation and theory that we see in this group discussion (e.g., even if the male dies, the genes have already been passed along) is preparation for the kind of self-monitoring that biologists do routinely.

Having emphasized the benefits of classroom discussion, however, we offer two cautionary notes. First, the discussion cited in the chapters is *guided* by teachers to achieve the desired learning. Using classroom discussion well places a substantial burden on the teacher to support skilled discussion, respond flexibly to the direction the discussion is taking, and steer it productively. Guiding discussion can be a challenging instructional task. Not all questions are good ones, and the art of questioning requires learning on the part of both students and teachers.¹⁰ Even at the high school level, Bain (see Chapter 4) notes the challenge a teacher faces in supporting good student questioning:

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| Sarena | Does anyone notice the years that these were written? About how old are these accounts? Andrew? |
| Andrew | They were written in 1889 and 1836. So some of them are about 112 years old and others are about 165 years old. |
| Teacher | Why did you ask, Sarena? |
| Sarena | I'm supposed to ask questions about when the source was written and who wrote it. So, I'm just doing my job. |

BOX 13-2 Supporting Skilled Questioning and Explaining in Mathematics Problem Solving

In the dialogue below, young children are learning to explain their thinking and to ask questions of each other—skills that help students guide their own learning when those skills are eventually internalized as self-questioning and self-explaining.

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| Teacher | Maria, can you please explain to your friends in the class how you solved the problem? |
| Maria | Six is bigger than 4, so I can't subtract here [pointing] in the ones. So I have to get more ones. But I have to be fair when I get more ones, so I add ten to both my numbers. I add a ten here in the top [pointing] to change the 4 to a 14, and I add a ten here in the bottom in the tens place, so I write another ten by my 5. So now I count up from 6 to 14, and I get 8 ones (demonstrating by counting "6, 7, 8, 9, 10, 11, 12, 13, 14" while raising a finger for each word from 7 to 14). And I know my doubles, so 6 plus 6 is 12, so I have 6 tens left. [She thought, "1 + 5 = 6 and 6 + ? = 12 tens. Oh, I know 6 + 6 = 12, so my answer is 6 tens."] |
| Jorge | I don't see the other 6 in your tens. I only see one 6 in your answer. |
| Maria | The other 6 is from adding my 1 ten to the 5 tens to get 6 tens. I didn't write it down. |
| Andy | But you're changing the problem. How do you get the right answer? |
| Maria | If I make both numbers bigger by the same amount, the difference will stay the same. Remember we looked at that on drawings last week and on the meter stick. |
| Michelle | Why did you count up? |

Palincsar¹¹ has documented the progress of students as they move beyond early, unskilled efforts at questioning. Initially, students often parrot the questions of a teacher regardless of their appropriateness or develop questions from a written text that repeat a line of the text verbatim, leaving a blank to be filled in. With experience, however, students become productive questioners, learning to attend to content and ask genuine questions.

Maria	Counting down is too hard, and my mother taught me to count up to subtract in first grade.
Teacher	How many of you remember how confused we were when we first saw Maria's method last week? Some of us could not figure out what she was doing even though Elena and Juan and Elba did it the same way. What did we do?
Rafael	We made drawings with our ten-sticks and dots to see what those numbers meant. And we figured out they were both tens. Even though the 5 looked like a 15, it was really just 6. And we went home to see if any of our parents could explain it to us, but we had to figure it out ourselves and it took us 2 days.
Teacher	Yes, I was asking other teachers, too. We worked on other methods too, but we kept trying to understand what this method was and why it worked. And Elena and Juan decided it was clearer if they crossed out the 5 and wrote a 6, but Elba and Maria liked to do it the way they learned at home. Any other questions or comments for Maria? No? Ok, Peter, can you explain your method?
Peter	Yes, I like to ungroup my top number when I don't have enough to subtract everywhere. So here I ungrouped 1 ten and gave it to the 4 ones to make 14 ones, so I had 1 ten left here. So 6 up to 10 is 4 and 4 more up to 14 is 8, so 14 minus 6 is 8 ones. And 5 tens up to 11 tens is 6 tens. So my answer is 68.
Carmen	How did you know it was 11 tens?
Peter	Because it is 1 hundred and 1 ten and that is 11 tens.

Similarly, students' answers often cannot serve the purpose of clarifying their thinking for classmates, teachers, or themselves without substantial support from teachers. The dialogue in Box 13-4 provides an example of a student becoming clearer about the meaning of what he observed as the teacher helped structure the articulation.

BOX 13-3 Questioning and Explaining in High School Science

The teacher passes out eight pages of case materials and asks the students to get to work. Each group receives a file folder containing the task description and information about the natural history of the ring-necked pheasant. There are color pictures that show adult males, adult females, and young. Some of the pages contain information about predators, mating behavior, and mating success. The three students spend the remainder of the period looking over and discussing various aspects of the case. By the middle of the period on Tuesday, this group is just finalizing their explanation when Casey, a member of another group, asks if she can talk to them.

Casey What have you guys come up with? Our group was wondering if we could talk over our ideas with you.

Grace Sure, come over and we can each read our explanations.

These two groups have very different explanations. Hillary's group is thinking that the males' bright coloration distracts predators from the nest, while Casey's group has decided that the bright coloration confers an advantage on the males by helping them attract more mates. A lively discussion ensues.

Ed But wait, I don't understand. How can dying be a good thing?

Jerome Well, you have to think beyond just survival of the male himself. We think that the key is the survival of the kids. If the male can protect his

Group work and group or classroom discussions have another potential pitfall that requires teacher attention: some students may dominate the discussion and the group decisions, while others may participate little if at all. Having a classmate take charge is no more effective at promoting metacognitive development—or supporting conceptual change—than having a teacher take charge. In either case, active engagement becomes unnecessary. One approach to tackling this problem is to have students rate their group effort in terms not only of their product, but also of their group dy-

- young and give them a better chance of surviving then he has an advantage.
- Claire Even if he dies doing it?
- Grace Yeah, because he will have already passed on his genes and stuff to his kids before he dies.
- Casey How did you come up with this? Did you see something in the packets that we didn't see?
- Grace One reason we thought of it had to do with the last case with the monarchs and viceroy.
- Hillary Yeah, we were thinking that the advantage isn't always obvious and sometimes what is good for the whole group might not seem like it is good for one bird or butterfly or whatever.
- Jerome We also looked at the data in our packets on the number of offspring fathered by brighter versus duller males. We saw that the brighter males had a longer bar.
- Grace See, look on page 5, right here.
- Jerome So they had more kids, right?
- Casey We saw that table too, but we thought that it could back up our idea that the brighter males were able to attract more females as mates.

The groups agree to disagree on their interpretation of this piece of data and continue to compare their explanations on other points. While it may take the involvement of a teacher to consider further merits of each explanation given the data, the students' group work and dialogue provide the opportunity for constructing, articulating, and questioning a scientific hypothesis.

namics.¹² Another approach, suggested by Bain (Chapter 4), is to have students pause during class discussion to think and write individually. As students discussed the kind of person Columbus was, Bain asked them to write a 2-minute essay before discussing further. Such an exercise ensures that students who do not engage in the public discussion nonetheless formulate their ideas.

Group work is certainly not the only approach to supporting the development of metacognitive skills. And given the potential hazard of group

BOX 13-4 Guiding Student Observation and Articulation

In an elementary classroom in which students were studying the behavior of light, one group of students observed that light could be both reflected and transmitted by a single object. But students needed considerable support from teachers to be able to articulate this observation in a way that was meaningful to them and to others in the class:

- | | |
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| Ms. Lacey | I'm wondering. I know you have a lot of see-through things, a lot of reflect things. I'm wondering how you knew it was see-through. |
| Kevin | It would shine just, straight through it. |
| Ms. Lacey | What did you see happening? |
| Kevin | We saw light going through the . . . |
| Derek | Like if we put light . . . |
| Kevin | Wherever we tried the flashlight, like right here, it would show on the board. |
| Derek | And then I looked at the screen [in front of and to the side of the object], and then it showed a light on the screen. Then he said, come here, and look at the back. And I saw the back, and it had another [spot]. |
| Ms. Lacey | Did you see anything else happening at the material? |
| Kevin | We saw sort of a little reflection, but we, it had mostly just see-through. |
| Derek | We put, on our paper we put reflect, but we had to decide which one to put it in. Because it had more of this than more of that. |
| Ms. Lacey | Oh. So you're saying that some materials . . . |
| Derek | Had more than others . . . |

dynamics, using some individual approaches to supporting self-monitoring and evaluation may be important. For example, in two experiments with students using a cognitive tutor, Aleven and Koedinger¹³ asked one group to explain the problem-solving steps to themselves as they worked. They found that students who were asked to self-explain outperformed those who spent the same amount of time on task but did not engage in self-explanation on transfer problems. This was true even though the common time limitation meant that the self-explainers solved fewer problems.

- Ms. Lacey . . . are doing, could be in two different categories.
- Derek Yeah, because some through were really reflection and see-through together, but we had to decide which.
- [Intervening discussion takes place about other data presented by this group that had to do with seeing light reflected or transmitted as a particular color, and how that color compared with the color of the object.]
- [at the end of this group's reporting, and after the students had been encouraged to identify several claims that their data supported among those that had been presented previously by other groups of students]
- Ms. Lacey There was something else I was kinda convinced of. And that was that light can do two different things. Didn't you tell me it went both see-through and reflected?
- Kevin & Derek Yeah. Mm-hmm.
- Ms. Lacey So do you think you might have another claim there?
- Derek Yeah.
- Kevin Light can do two things with one object.
- Ms. Lacey More than one thing?
- Kevin Yeah.
- Ms. Lacey Okay. What did you say?
- Kevin & Derek Light can do two things with one object.

See Chapter 10 for the context of this dialogue.

Another individual approach to supporting metacognition is suggested by Stewart (Chapter 12). Students record their thinking early in the treatment of a new topic and refer back to it at the unit's end to see how it has changed. This brings conscious attention to the change in a student's own thinking. Similarly, the reflective assessment aspect of the ThinkerTools curriculum described in Chapter 1 shifts students from group inquiry work to evaluating their group's inquiry individually. The results in the ThinkerTools case suggest that the combination of group work and individual reflective

assessment is more powerful than the group work alone (see Box 9-5 in Chapter 9).

PRINCIPLES OF LEARNING AND CLASSROOM ENVIRONMENTS

The principles that shaped these chapters are based on efforts by researchers to uncover the rules of the learning game. Those rules as we understand them today do not tell us how to play the best instructional game. They can, however, point to the strengths and weakness of instructional strategies and the classroom environments that support those strategies. In Chapter 1, we describe effective classroom environments as learner-centered, knowledge-centered, assessment-centered, and community-centered. Each of these characteristics suggests a somewhat different focus. But at the same time they are interrelated, and the balance among them will help determine the effectiveness of instruction.

A community-centered classroom that relies extensively on classroom discussion, for example, can facilitate learning for several reasons (in addition to supporting metacognition as discussed above):

- It allows students' thinking to be made transparent—an outcome that is critical to a learner-centered classroom. Teachers can become familiar with student ideas—for example, the idea in Chapter 7 that two-thirds of a pie is about the same as three-fourths of a pie because both are missing one piece. Teachers can also monitor the change in those ideas with learning opportunities, the pace at which students are prepared to move, and the ideas that require further work—key features of an assessment-centered classroom.
- It requires that students explain their thinking to others. In the course of explanation, students develop a disposition toward productive interchange with others (community-centered) and develop their thinking more fully (learner-centered). In many of the examples of student discussion throughout this volume—for example, the discussion in Chapter 2 of students examining the role of Hitler in World War II—one sees individual students becoming clearer about their own thinking as the discussion develops.
- Conceptual change can be supported when students' thinking is challenged, as when one group points out a phenomenon that another group's model cannot explain (knowledge-centered). This happens, for example, in a dialogue in Chapter 12 when Delia explains to Scott that a flap might prevent more detergent from pouring out, but cannot explain why the amount of detergent would always be the same.

At the same time, emphasizing the benefits of classroom discussion in supporting effective learning does not imply that lectures cannot be excellent pedagogical devices. Who among us have not been witness to a lecture from which we have come away having learned something new and important? The Feynman lectures on introductory physics mentioned in Chapter 1, for example, are well designed to support learning. That design incorporates a strategy for accomplishing the learning goals described throughout this volume.¹⁴ Feynman anticipates and addresses the points at which students' preconceptions may be a problem. Knowing that students will likely have had no experiences that support grasping the size of an atom, he spends time on this issue, using familiar references for relative size that allow students to envision just how tiny an atom is.

But to achieve effective learning by means of lectures alone places a major burden on the teacher to anticipate student thinking and address problems effectively. To be applied well, this approach is likely to require both a great deal of insight and much experience on the part of the teacher. Without such insight and experience, it will be difficult for teachers to anticipate the full range of conceptions students bring and the points at which they may stumble.¹⁵ While one can see that Feynman made deliberate efforts to anticipate student misconceptions, he himself commented that the major difficulty in the lecture series was the lack of opportunity for student questions and discussion, so that he had no way of really knowing how effective the lectures were. In a learner-centered classroom, discussion is a powerful tool for eliciting and monitoring student thinking and learning.

In a knowledge-centered classroom, however, lectures can be an important accompaniment to classroom discussion—an efficient means of consolidating learning or presenting a set of concepts coherently. In Chapter 4, for example, Bain describes how, once students have spent some time working on competing accounts of the significance of Columbus's voyage and struggled with the question of how the anniversaries of the voyage were celebrated, he delivers a lecture that presents students with a description of current thinking on the topic among historians. At the point at which this lecture is delivered, student conceptions have already been elicited and explored. Because lectures can play an important role in instruction, we stress once again that the emphasis in this volume on the use of discussion to elicit students' thinking, monitor understanding, and support metacognitive development—all critical elements of effective teaching—should not be mistaken for a pedagogical recommendation of a single approach to instruction. Indeed, inquiry-based learning may fall short of its target of providing students with deep conceptual understanding if the teacher places the full burden of learning on the activities. As Box 1-3 in Chapter 1 suggests, a lecture that consolidates the lessons of an activity and places the activity in the

conceptual framework of the discipline explicitly can play a critical role in supporting student understanding.

How the balance is struck in creating a classroom that functions as a learning community attentive to the learners' needs, the knowledge to be mastered, and assessments that support and guide instruction will certainly vary from one teacher and classroom to the next. Our hope for this volume, then, is that its presentations of instructional approaches to addressing the key principles from *How People Learn* will support the efforts of teachers to play their own instructional game well. This volume is a first effort to elaborate those findings with regard to specific topics, but we hope it is the first of many such efforts. As teachers and researchers become more familiar with some common aspects of student thinking about a topic, their attention may begin to shift to other aspects that have previously attracted little notice. And as insights about one topic become commonplace, they may be applied to new topics.

Beyond extending the reach of the treatment of the learning principles of *How People Learn* within and across topics, we hope that efforts to incorporate those principles into teaching and learning will help strengthen and reshape our understanding of the rules of the learning game. With physics as his topic of concern, Feynman¹⁶ talks about just such a process: "For a long time we will have a rule that works excellently in an overall way, even when we cannot follow the details, and then some time we may discover a *new rule*. From the point of view of basic physics, the most interesting phenomena are of course in the *new* places, the places where the rules do not work—not the places where they *do* work! That is the way in which we discover new rules."

We look forward to the opportunities created for the evolution of the science of learning and the professional practice of teaching as the principles of learning on which this volume focuses are incorporated into classroom teaching.

NOTES

1. Egan, 1986.
2. Story summarized by Kieran Egan, personal communication, March 7, 2003.
3. Liping Ma's work, described in Chapter 1, refers to the set of core concepts and the connected concepts and knowledge that support them as "knowledge packages."
4. Griffin and Case, 1995.
5. Moss and Case, 1999.
6. Kalchman et al., 2001.
7. Palincsar, 1986; White and Fredrickson, 1998.
8. Ma, 1999, p. 5.
9. Ma, 1999, p. 9.

10. Palincsar, 1986.
11. Palincsar, 1986.
12. National Research Council, 2005 (Stewart et al., 2005, Chapter 12).
13. Aleven and Koedinger, 2002.
14. For example, he highlights core concepts conspicuously. In his first lecture, he asks, "If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis that all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.
15. Even with experience, the thinking of individual students may be unanticipated by the teacher.
16. Feynman, 1995, p. 25.

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