

Part 2

What Does Inquiry Look Like?

Science As Argument and Explanation: Exploring Concepts of Sound in Third Grade

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It is part of the educator's responsibility to see equally to two things: First, that the problem grows out of the conditions of the experience being had in the present, and that it is within the range of the capacity of students; and, secondly, that it is such that it arouses in the learner an active quest for information and for production of new ideas. (Dewey, 1938/1963, p. 79)

INTRODUCTION

The active quest for information and for production of new ideas characterizes inquiry-based science classrooms. Many elementary school science classrooms have moved beyond a didactic orientation where they present science content and test for understanding through recall questions (Anderson & Smith, 1987). They have adopted science curriculum materials that engage students in first-hand experiences with phenomena. However, these activity-driven approaches, as Anderson and Smith observed in 1987, typically involve students in activities but offer them few opportunities to develop conceptual understandings. The *National Science Education Standards* published by the National

Research Council (NRC) in 1996 assert that teachers must promote inquiry in science classrooms. In particular the *Standards* challenge teachers to provide less emphasis on “science as exploration and experiment” and more emphasis on “science as argument and explanation” (p. 113).

What does an inquiry-based classroom look like? What are reasonable expectations for such classrooms?

J. J. Schwab addressed these issues in 1962:

With classroom materials converted from a rhetoric of conclusions to an exhibition of the course of enquiry, conclusions alone will no longer be the major component. Instead, we will deal with units which consist of the statement of a scientific problem, a view of the data needed for its solution, an account of the interpretation of these data, and a statement of the conclusions forged by the interpretation. Such units as these will convey the wanted meta-lesson about the nature of enquiry. (pp. 52-53)

Schwab described a process of classroom inquiry that includes finding problems, collecting and interpreting data, and forging conclusions. This sounds very much like “science as exploration and experiment.” Schwab’s description fails to provide an adequate portrayal of inquiry in classrooms devoted to “science as argument and explanation.” The purpose of this chapter is to provide stories from real classrooms that illustrate inquiry-based instruction emphasizing argument and explanation so that we can more completely understand what might be reasonable expectations for such classrooms.

SETTING THE CONTEXT

These stories take place in two different third-grade classrooms in two elementary schools not far from a large research university. In each classroom the teaching was shared by the classroom teacher, either Anderson or Chezem, and a university teacher educator, Abell, who had been released from her university teaching responsibilities to share the work of teaching elementary science in these two schools. Shared teaching meant that we—Chezem and Abell, or Anderson and Abell—collaborated over the course of several units of instruction in the planning and enactment of science instruction, including assessing students and reflecting on our teaching. (Other examples of shared science teaching can be found in Abell and Roth [1995] and Abell et al., [1996]).

The stories of our science teaching occurred during two separate teaching events, the first in the spring at Chezem's school, followed by another in the fall at Anderson's. Each teaching team had independently decided to concentrate on the topic of sound for a third-grade unit of science instruction. We deemed this topic age appropriate and offering many opportunities for inquiry. We planned to develop a community of inquiry in these classes by involving students in first-hand experiences supported by "scientists meetings" (Reardon, 1993), where teachers would help students think through, share, and compare their science ideas.

As we started planning our units on sound, we consulted the *Benchmarks for Science Literacy*, issued in 1993 by the American Association for the Advancement of Science (AAAS), and the *National Science Education Standards* (NRC, 1996). These documents declare that:

By the end of the second grade, students should know that:

- ▶ Things that make sound vibrate. (AAAS, 1993, p. 89)

As a result of the activities in grades K-4, all students should develop an understanding of:

- ▶ Position and motion of objects
- ▶ Sound is produced by vibrating objects. (NRC, 1996, pp. 123, 127)

Thus in both classes we began our inquiry into sound by examining the concept of vibration. The reform documents make teaching the concept seem quite clear cut; the chapter on "The Research Base" in the *Benchmarks* does not mention problems students might have in understanding it. The *Standards* did add one caveat: "Sounds are not intuitively associated with the characteristics of their source by younger K-4 students, but that association can be developed by investigating a variety of concrete phenomena toward the end of the K-4 level" (NRC, 1996, p. 126). Thus we proceeded on the assumption that exposing students to many sound phenomena would contribute to their conceptual understanding of sound and vibration.

Next came examining published science curricula that address the topic of sound. Many of the science curricula we examined seemed to agree that the relationship between sound and vibration could be developed by investigating a variety of phenomena. In the "Sounds" unit in *Science & Technology for Children*, a curriculum published by the National Science Resources Center in 1991, students explore vibrating rulers and vocal cords. The unstated assumption is that

they will see a connection between sound and vibration. In the *Full Option Science System* “Physics of Sound” module developed by the Lawrence Hall of Science (1992), students observe sound originating from a variety of vibrating sources, including tuning forks, string phones, water bottles, and xylophones. In the *Insights* “Sound” module published by the Education Development Center in 1991, students are taken through a learning experience in which they explore vibrations with drums, tuning forks, and rubber bands. Accompanying the *Insights* investigations are suggestions for classroom discussions. In the culminating discussion the teacher is directed to “Explain that some vibrations are so small and/or fast that they can’t be seen or felt” (p. 109). This was the only indication in any of the curriculum materials examined that the concept of vibrations might be a problem for students. The stories told here unfold against this backdrop of our preparations to teach the sound unit.

STORY #1: OPENING THE CLASSROOM TO ARGUMENT AND EXPLANATION

We (Chezem and Abell) introduced our unit on sound with a large group activity on feeling various parts of your body—lips, nose, throat—while you vocalize. Whereas some students used words like “moving” and “tickling” to describe the sensation, one student, Tyler, used the words “vibration” and “wave” in his answers. Next, students interacted at several exploratory stations at which they were presented with vibration phenomena: rubber bands, rulers, cans covered with balloons, and dancing rice. The rice proved most interesting to the students. At the station we placed rice on plastic wrap affixed to the top of a plastic bowl. When students banged the bottom of a metal pan, open end facing the bowl, the rice danced. During the scientists meeting that followed, Cindy explained that the sound traveled to the bowl and made the rice jump. We were surprised to hear this sophisticated reason so early in the lesson and wondered how other students were interpreting their observations.

The next lesson engaged students in explorations with tuning forks: “Try touching the tuning fork to your set of materials and see what happens.” Students were excited when they placed a vibrating tuning fork on a plastic cup, water, and a ping pong ball. They observed the cup buzzing, the water jumping, and the ping pong ball bouncing. At the end of the lesson students came together to share their observations, which we summarized on a class chart.

Up to this point in our instruction, we had emphasized science as exploration. Students had explored various phenomena and we had summarized

their observations. We knew we must now engage students in discussions in which they would invent explanations to account for their observations. Where such a discussion would lead us, we could only guess. At our next class meeting we synthesized student observations and asked for explanations: “Why do you think that happened?” we asked. John fixed his explanation on the vibration of the tuning fork and the transfer of the vibration to another object. When we asked students to find other instances of this transfer phenomenon, we noticed they could not give examples other than the observations from the tuning fork explorations.

To give students an opportunity to represent their ideas in another way, we instructed them, “Draw a picture of how something makes a sound and how you hear it.” Several groups drew a textbook-looking “wave” picture to represent sound between the sound maker and the listener. We wondered where that idea came from. Cindy and Bobby drew a picture of two children talking on a string telephone. They drew a jagged line to represent the sound across the string. When asked what was going on in their picture, Cindy replied that the sound was moving along the string. Bobby corrected her, saying that it was the vibration in the string. Two other groups drew stereos with sound “lines” coming out of them. When John’s group was probed about the lines, this conversation ensued:

Teacher: What are those lines?

John: Well, in my stereo there is a laser that plays CDs.

Teacher: What do you think is happening in the speaker? Have you ever seen the inside of a speaker?

John: There are lots of wires.

Teacher: Anything else?

John: A big round thing.

Teacher: What happens to that round thing when sound comes out of the speaker?

John: It moves in and out.

Later, during scientists meeting, John described how speakers move when sounds are being made. He embellished the description with a story about his uncle’s truck, where the speakers do not have covers. According to John, not only do the speakers move when music is played, but they move more if the volume is turned up.

After explorations of sound traveling through different media—air, water, string, and wood—we asked students to represent their ideas in another way. We gave each team this assignment:

Your job as a team is to write three sentences about sound that you can agree about. You can base your sentences on any of the investigations we have tried. Each team member will write one sentence. The others will help.

Their sentences mentioned vibrations, sound traveling, and hearing sounds. Some sentences referred to activities we had done in class, others to everyday life:

- ▶ Sound can travel through almost anything.
- ▶ The catcher [pinna] catches everything you hear such as a dog barking.
- ▶ If you put your ear against the ground you can hear vibration.
- ▶ Cars make different sounds.
- ▶ Sound doesn't travel very good in air.
- ▶ Sound is traveling through the air all the time.
- ▶ If you put your hand on your throat and talk you can feel vibration.
- ▶ Sound travels better through wood and [string] telephone than air.
- ▶ It vibrates when it goes through something.
- ▶ Sound can be loud or soft.
- ▶ Sound travels and vibrates when you sing or talk.
- ▶ If you put something close to your ear you could hear it very good.
- ▶ It's like a vibration.
- ▶ When you touch your Adam's apple and talk you can feel it vibrating.
- ▶ When something hits something it makes a sound or it vibrates and makes a sound.
- ▶ When you talk the sound vibrates and goes to your ears.

We consolidated the sentences into a set of ten statements and displayed them on a large chart. Our plan was to ask students to agree or disagree with each statement and give evidence for their thinking. We thought that everyone could readily agree upon the first statement: “Sound is made when a thing vibrates.” After all, most of our explorations and interactions had demonstrated just this idea. What a surprise when a number of students disagreed with the statement! We asked for their evidence. They began to present what to them were disconfirming cases. Mandy said, “If you stomped on the ground, you would hear a sound but the ground would not vibrate.” We asked Mandy and a

few others to pretend they were buffalo scouts, ears to the floor, to find out whether they could feel the stampeding buffalo feet of the rest of us. They did, but were not convinced. Mark offered another example. “What about if two cars crashed? There would be a loud sound, but the cars would not vibrate.” From their own experiences with car accidents, several students offered evidence contrary to Mark’s statement. Mark seemed unconvinced. As teachers we left class that day wondering how the lesson had gotten so far off track. Or had it?

Reflection

In this story, we as teachers started from a stance of science as exploration and experiment. That is, we began by having students explore a series of vibration phenomena. Tyler’s answer concerning vibrations in the first activity of the unit, and our early examination of curriculum materials and standards documents, brought us to assume that getting to the concept would be an easy journey. But when we at last opened the classroom to argument and explanation, we found out some things about the students’ thinking that surprised us. We learned that students did not all readily agree that “Sound is produced by vibrating objects.” Their collective theory more likely resembled this variation: “Some sounds are produced by vibrating objects.”

Our original orientation to science as exploration and experiment did not help students grasp the concept we were addressing in our instruction, nor did it reveal to us anything about student understanding. When we opened the classroom to argument and explanation, things changed. We found that students had constructed a diversity of ideas about sound. Some had separated science class phenomena like tuning forks from real-world phenomena like stomping feet or crashing cars. By the end of the sound unit, many students still held two theories for sound, one for class phenomena and one for events in the real world. We also found out that, even when their theories did not match the scientifically accepted one, the third graders were capable of developing explanations that fit the evidence, of finding discrepant data, and of arguing for and against certain theories. What we learned would prove fruitful the next time we attempted teaching a unit about sound.

STORY #2: ASKING STUDENTS TO EXPLAIN AND CHOOSE THEORIES

The following fall another teaching team (Anderson and Abell) in a different school used these new understandings to design and enact a unit on sound with another third-grade class. This time we wanted to begin the unit by bringing the real world into the science class, trying to avoid the dichotomy between real world and school science observed in the spring. We conducted a brainstorming session in which students created a class list of things that make sounds. Their list included barking dogs, crying babies, computers, CD players, and many more. We again wanted to provide experiences with sounds and vibrations that would lead to opportunities for argumentation and explanation. Thus in the second lesson, we engaged students in activities with rubber bands, drums, tuning forks and so forth. At the end of the session, we asked students to write a rule for sound based on their observations. Every student's rule mentioned vibration: "The sounds are made by vibrations"; "When someone or something makes a sound, it vibrates"; "Things vibrate."

The third lesson began with the request, "Think of the most unusual tuning fork experiment you did in team work yesterday, and we're going to ask you to share that and show us what happened." Students willingly shared their most interesting experiences with the tuning forks.

"If you touch it right here [to water], it makes it um, kind of vibrate."

"We're going to, Cody's going to hit the tuning fork and we're going to put it against the table and it will shock the table."

"They're putting the tuning fork on Luke's glasses and they're making the glasses vibrate."

We then encouraged students to see patterns in the findings.

Teacher: We saw a lot of different things. Did you notice anything the same about what your group tried? Cherril.

Cherril: Almost all of them vibrated.

Teacher: You know what I'm wondering about is maybe we should all agree on what "vibrate" means. Do we all mean the same thing when we say "vibrate?" What did you mean, Cherril?

Cherril: (shrugs)

Teacher: Can you think of another word that you might use instead of “vibrate?” What about the rest of you? A lot of you have used this word the past couple of days, but what do you mean by that? Cherril?

Cherril: Movement.

Teacher: Movement. Timothy?

Timothy: Moving back and forth.

Teacher: Moving back and forth. So you say “movement” and he says “moving back and forth.” What about you, Rachel?

Rachel: Moving fast

Teacher: OK, so moving fast. Cody?

Cody: It’s not going very far.

Teacher: So, it’s not going far but it’s moving a little bit. Anybody else about vibrate? Ronny?

Ronny: Shaking like this.

Teacher: Shaking, that’s nice. Sounds like you’re all saying something about moving and something about back and forth like Timothy said. And maybe not moving a lot, but a little bit. Sounds like we agree on what “vibrating” means. OK, then let’s go back to the tuning fork idea. Cherril said, tell us what you said again about...

Cherril: Almost all of them vibrated.

Teacher: So, almost all, that must mean that one of them didn’t vibrate and I’m wondering if you can think of any instances that didn’t vibrate. That didn’t move or shake.

Although the class had established a shared meaning of “vibration,” we remembered that not all students in the spring class had completely bought into the notion that sounds are produced by vibration. Cherril’s final comment was a clue that we would need to probe a little farther. So we returned to the list of sounds we had made in the first activity and the rules for sound students had developed the day before.

Teacher: The other day your sound rules all mentioned that vibration causes sound. Now let’s go back and look at our list of sounds. We’ve got over fifty sounds up there. Why don’t you look through them and see if you can find anywhere you think the sound is not caused by vibrations.

Hands flew up. Every student had an opinion. Nicole said that singing birds would not vibrate. Rachel's choice was a crying baby and Luke's a computer. Several other candidates for lack of vibration were mentioned. We next asked students: "How could we test this to be sure that there is no vibration involved? How could we find out?" Lucy mentioned putting a CD in a player and then plugging it in to see whether it vibrated. Lon suggested trying the computer right there in the room. He popped up and approached the computer with his hand out. The classroom quieted down so that only the humming of the computer could be heard. Lon placed his hand on the computer and nodded, "It's vibrating all right." Then we gave the students some homework: "Here are some things that you don't think vibrate when they make a sound: birds, cats, a baby crying. Those would be some things that you could actually try and test and see what you think."

While students went home to test these possibly disconfirming cases, we teachers went home to think about what had happened and what to do next. One of us had attended a seminar about children's theory choice (cf. Samarapungavan, 1992), which challenged our thinking. Perhaps in settling on disconfirming cases as the main way to convince students to revise their theories, we were going down the wrong road. After all, the literature strongly supported the idea that anomalous data alone would be insufficient to help students change their theories (Chinn & Brewer, 1993; Tasker & Freyberg, 1985). And, we had seen this play out in a real classroom in the spring when, despite evidence to the contrary, students like Mandy and Mark did not agree that sounds are produced by vibration.

We decided to switch from a strategy of disconfirming to a theory-choice strategy. In the next lesson, we provided three theories among which students could select: all sound is caused by vibration; some sounds are caused by vibration and some are not; some sounds are caused by vibration and some are caused by something else. At our next class meeting, the three theories were posted on the board and students were asked to decide which one they thought best explained what they knew about sound. We asked students to vote by secret ballot for their favored theory. The first theory received three votes, the second five, and the last twelve. "Is this like the election earlier this month? Should the theory with the most votes be accepted as the winner?" we asked. Cody responded, "You have to prove it in science." We asked each student to turn to the person sitting in the next seat and present some evidence from one of our investigations that would support the theory the student selected. This was very difficult for the students. Only Josh was

able to build a case in support of the first theory, citing evidence from the tuning fork investigations.

We retreated from the theory-choice strategy and refocused students on the next part of the lesson. We asked them to draw pictures of what they thought happens when a sound is made and heard. Three of the teams drew nothing in between the sound maker and the ear. Two teams drew the textbook version of sound waves radiating from the sound source. Five other teams drew something else between the source and the ear: horizontal squiggly lines, vertical squiggly lines, or, in one case, a tunnel from a radio to an ear labeled “sound.” When asked to explain their lines, many students used the term “sound waves” but when probed about what a sound wave could be, they did not have a response. Except for Josh. He stated that the air was moving and that moving air was being passed along as a person talked.

The final first-hand experience of our sound unit concerned sound traveling through solids, liquids, and gases. In our scientists meeting we discussed two different explanations to account for how the sound gets through the material:

- ▶ Sound waves are vibrations of water or air or wood.
- ▶ Sound waves are pieces of sound going through water or air or wood.

Six of nine teams supported the first explanation, using evidence from many different class experiences. The three groups who were in favor of a particle theory of sound had trouble supporting their position with evidence. These ideas led us back to the question about sound and vibration and to the activity of the day before. To bring closure to our sound inquiries, we asked students to choose between two theories of sound:

- ▶ All sounds are caused by vibration.
- ▶ Some sounds are caused by vibration.

In the end there was still a split decision, although more students than the day before selected the first theory. As teachers we were left with the need to reflect upon our experiences as we prepared for our next unit of instruction.

Reflection

In planning and enacting this sound unit, we based several changes on what we had learned from the spring teaching team. We tried to incorporate real-world experiences throughout the unit, not relying only on the science class equipment and experiments in discussions. We also brought argumentation into play

earlier in the unit, asking students to predict and test disconfirming cases. And we added to our teaching repertoire a theory-choice strategy on comparing alternative explanations.

When we gave students the freedom to argue and explain what made sense to them, as teachers we had to be willing and able to listen to their arguments and explanations and try to understand them. We also had to be willing to let those science conversations be a major driving force in planning and enacting our science lessons. When we turned our classroom over to argument and explanation, we lost some of our control over the instruction. We could not always predict where the lesson would end up. Perhaps most difficult of all was that we had to accept that not all students finally agreed to the scientific explanation of sound and vibration.

CONCLUSION

Our teaching stories include two classrooms moving from science as exploration and experiment to science as argument and explanation as they inquired into concepts of sound. Science knowledge, as J. J. Schwab observed in 1962, originates in the “united activities of the human mind and hand” (p. 102). In our classrooms, students built knowledge from both their first-hand experiences with phenomena and their discussions with other students and with the teachers, what in everyday parlance is referred to as hands-on and minds-on instruction.

Though not all of the students came away with the accepted scientific notions about sound, they did all have opportunities to have first-hand experiences with science phenomena and to talk about their evolving science ideas. According to Freyberg and Osborne in an essay of 1985, it is reasonable that we would have differentiated goals for a class of students. Specifically they suggest that:

The aim of science education for children should be to ensure that they are *all* encouraged: (i) to continue to investigate things and explore how and why things behave as they do, and (ii) to continue to develop explanations that are sensible and useful to them. (p. 90)

We want *many* children:

(iii) to recognize that scientists have sensible and useful ways of investigating things, many aspects of which apply not just to science, and (iv) to regard at least some scientific explanations as intelligible and plausible and as potentially useful to society, if not to the child personally. (p. 90)

We can expect *some* children:

(v) to replace their own intuitive explanations with, or to evolve their own ideas towards, the accepted explanations of the scientific community, and (vi) to become committed to the endeavours of advancing scientific knowledge still further. (p. 90)

If we accept these goals, we should feel satisfied with the outcomes witnessed in the sound stories. In the end, not every student understood or believed that all sounds are made by vibrating objects, but they all had opportunities to investigate, to invent sensible explanations, and to develop arguments in support of their explanations. We hope that these students, for whom the process of argumentation and explanation in science class was new, learned something valuable about making sense of their world. We expect they will continue to use these processes to inquire into natural phenomena. As science teachers we learned to provide opportunities not only for first-hand investigations but also for classroom discussions that emphasize argument and explanation. We continue to learn how to accept our students' ideas, trusting that those ideas represent what makes sense to students at a given point in the development of their scientific thinking.

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Designing Classrooms That Support Inquiry¹

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A continuing point of debate, among both developmental psychologists and science educators, is over the appropriateness of the metaphor of the child-as-scientist. This metaphor suggests that children seek knowledge about the world as scientists do, generating and exploring hypotheses about phenomena, and constructing consistent and coherent theories about the world (Brewer & Samarapungavan, 1991). On the other side are researchers (e.g., Kuhn et al., 1995) who emphasize the stark contrasts between the reasoning processes employed by scientists and those routinely used by laypeople. According to Kuhn et al., even adults if they lack scientific training routinely distort evidence to preserve favored theories and make a number of systematic errors in the generation and interpretation of evidence.

In considerations about the science education of young children, these positions are sometimes played out as extremes. Often the debates refer to the same source. The work of the Swiss epistemologist Jean Piaget on infants' early mental development and its roots in exploration and actions on the world (Piaget, 1952), for example, is sometimes used to justify a rather romantic trust in the power of children's curiosity. Yet Inhelder and Piaget's (1958) pioneering work on the development of logical thinking has been invoked to justify the restriction of

early science education programs to the kinds of activities for which children are presumably ready at the moment. In practice, this has often meant limiting elementary school science to the mere introduction of facts and simple relationships, supplemented, perhaps, by domain-general exercises in reasoning—such as categorization and transitive reasoning in the early grades and process skills like observation and measurement in the later grades. As Metz (1995) argues convincingly, the notion that genuine inquiry should wait until children are “developmentally ready” often rests on misunderstandings about young children’s capabilities and the nature of inquiry in the sciences. But neither is curiosity sufficient in itself. Although children’s curiosity is certainly the foundation upon which good science instruction builds, it is equally important to understand the forms of support that teachers deploy to stretch initial interests into sustained and fruitful programs of inquiry.

Our own position, consistent with the *National Science Education Standards* (National Research Council, 1996), is that “science as inquiry is basic to science education and a controlling principle in the ultimate organization and selection of students’ activities” (p. 105). In our view, the interesting question is not whether children have some developmental capability to engage in genuine inquiry. Rather than regarding children’s capabilities as inherent and presumably fixed, we understand thinking and reasoning as grounded within contexts that are inherently social, not naturally occurring. Thus, thinking is brought into being and develops within contexts that are fashioned by people. Whether or not we are aware of it, these contexts include norms for the kinds of questions worth pursuing, the activities that are valued, the forms of argumentation deemed convincing, and the criteria for a satisfactory explanation. Recalling that learning environments are designed (Glaser, 1976; Lehrer & Schauble, in press; Simon, 1981) helps to turn our attention to the “design tools” that we have available for making classrooms and other learning contexts effective (Carpenter & Lehrer, in press). If teachers are the designers of learning environments, what kinds of design tools do they have at hand for fostering inquiry in the early grades?

These questions are the topic of collaborative investigation among a community of elementary grade teachers in the school district where we conduct our research. A rural and suburban district about fifteen miles from the state capital, it is undergoing extremely rapid growth in both the number and the diversity of its students. Teachers representing all five grades at the district’s four elementary schools work with us as co-researchers on a project aimed toward improving mathematics and science instruction. Teachers cooperate in learning to teach such new forms of mathematics as geometry, data, measure, and probability and to

understand the development of student thinking in these understudied topics. The other major initiative of the project is to learn how students can use these mathematical resources to understand science, especially through approaches that emphasize the development, evaluation, and revision of models.

We will begin our consideration of designing classrooms for inquiry by following one of these teachers as she orchestrates a long-term investigation in her first-grade class. The teacher used questions, forms of argumentation, and inscriptions to build on students' curiosity, turning their thinking toward important ideas like comparison, measure, and mechanism. In the second part of the paper, we consider ways that teachers of older elementary grade students can provide challenge and lift for students in grades three through five.

INQUIRY IN THE FIRST GRADE: DECOMPOSITION

We begin by summarizing the chain of inquiry conducted in one first-grade classroom, where children's curiosity about changes in the color of apples kicked off a year-long investigation into conditions for decomposition and explanations of it. Although this cycle of inquiry was initiated by children, it was sustained through the work of the teacher, Angie Putz. Over the course of the year, what started as a simple question led to opportunities to explore ideas related to experimentation, the role of models in scientific inquiry, and the importance of inscribing observations.

Investigating Ripening

As the class convened in the fall, Ms. Putz asked students to bring apples to class. As they inspected and described the variety of colors and shapes, someone pointed out that apples change color as they ripen. Ms. Putz asked children how they might account for this change, and a few children suggested that the sun might be the agent. Ms. Putz countered by asking children whether they could think of a way to find out more about how the sun affects fruit. We have found that this cycle of teacher questions following students' questions is quite common and important for modeling inquiry. The children in Ms. Putz's class proposed that they could investigate that idea by observing fruit in the sun. After some consideration, they agreed that bananas or tomatoes would be good candidates, because children knew that both of these fruits noticeably ripen.

The idea of a test. The next day, Ms. Putz brought green tomatoes to class and asked, "How do you think the sun helps in changing the colors?" Most students

responded that the sun “gives light.” The teacher asked children how they thought they might test their idea. Notice how her question raised the stakes, implying that beliefs about a phenomenon need to be justified by a particular form of argument—the test. Without such prodding, students rarely move beyond simple assertions. Valuing forms of argumentation and justification like these is a design tool that effective teachers like Ms. Putz employ for rendering inquiry productive.

In response to Ms. Putz’s query, several children suggested placing one tomato on the window sill and another in the dark. After some discussion about what would count as “dark,” the children settled on a spot in the classroom under a cover. They readily agreed that if they observed a tomato in each location, they would then know whether or not light mattered for effecting color change. However, one child, Ben, objected, “But the sun is hot. Does heat matter?”

Several children found Ben’s suggestion compelling. Once again, their teacher reoriented this discussion into a consideration of evidence and argument: “How could you test the role of heat?” Children suggested placing one tomato in the refrigerator. At this point in the discussion, the students were assuming that the tomato on the window sill could serve as the case testing the role of warmth. Here, Ms. Putz stepped in again, to help children elaborate their thinking about the factors that might be regulating the changes in color. She began to probe in ways that might help them untangle their original confounding of warmth and light. She asked, “How do you know that the window is the warmest place in the room?” Some students claimed that since this spot was closest to the sun, it was obviously the warmest. Others, thinking about proximity to the window during a cold Wisconsin fall, weren’t so sure. How could this disagreement be resolved? One child’s proposal that the class use a thermometer sparked a long discussion about how this measurement device might work (a discussion that we do not recount here). As a result of their explorations with the thermometer, children eventually settled on four conditions for observation, affording comparisons of light and heat. Their observational conditions were: light and cool (the windowsill), light and warm (a location away from the windowsill but still receiving a lot of sunlight), dark and warm (the covered tomato), and dark and cold (inside the refrigerator).

From observation to inscription. Ms. Putz next encouraged children to move beyond observation toward inscription. We propose children’s inscriptions as an important design tool of fundamental importance. As Latour has explained (1990), even though we think of scientists as observing the world, scientists do not do the bulk of their work with raw observations. Instead, they most often work with inscriptions, which may include records, drawings, mathematical formulae,

various kinds of output from instruments, and more. Choices of inscription are partly choices about what to preserve—inscriptions select and enhance information that is vital and leave out other information deemed unimportant. This fixing of experience provides a means of making public what all know consensually and of holding steady what unaided memory will lose or distort. Here, children decided to use drawings, a decision that provoked discussions about what changes should be represented and how these changes should be displayed. In this case, children decided to preserve a record of changes in the tomatoes over time.

Over the course of a few weeks, many children began to note a progressive discoloration, discharge, and change in how the tomatoes felt (as one described it, they became “squishy”). Discoloration was relatively easy to represent in drawings, but changes resulting from discharge and corresponding loss of turgidity were more difficult. Children settled upon a convention of using shadings of color to represent regions of “squishiness.” There was much discussion in the classroom about how to use detail to capture the changes observed. Ms. Putz and her students were surprised about the number of decisions that needed to be made to translate from the mind’s eye to an inscription of change that carried shared meaning for the class. Ms. Putz, of course, also knew that all of this careful observation and detailed inscription would focus children on transitions over time. The inscriptions served as the basis for comparing the contrasting conditions of light and temperature. Note that inscriptions confer the additional bonus of rendering public, shareable, and inspectable, the private thinking of individuals. A teacher who is aware of how children think has a considerable advantage in crafting instruction that is tuned to children’s understanding.

Children’s initial conjectures about light were confirmed, but many were surprised by the role of temperature: “Hey, Ms. Putz, that’s sort of a pattern! The tomato in the window was colder, so it took longer to change. The same thing happened to the tomato in the fridge.” Margaret added to this idea, commenting on the tomato in the refrigerator and the one in the dark place in the room: “Of all the tomatoes, these two changed the slowest.” Ms. Putz pushed further for explanation, asking, “Why do you think that?”

Margaret replied, “Because the other tomatoes changed faster because they had light.”

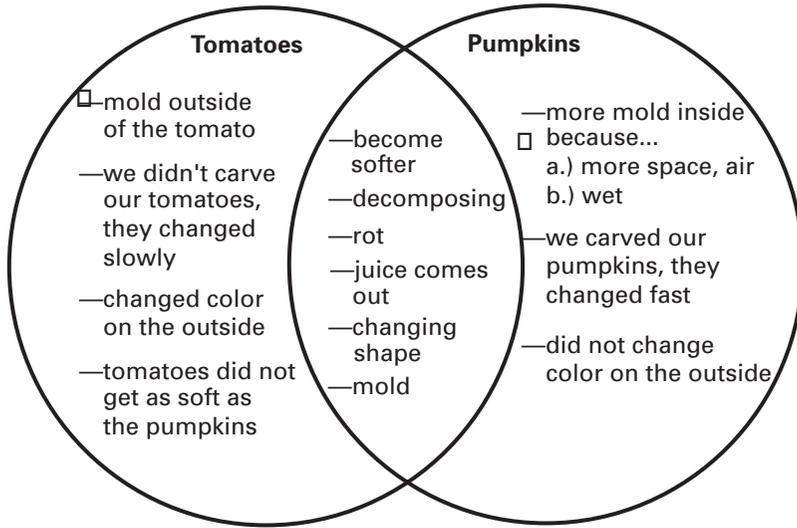
Finding this statement somewhat ambiguous, Ms. Putz gently challenged Margaret’s statement: “So does this mean that light is the only factor in the changing color?” This question led to a conversation during which children compared their four locations and decided that the fastest change was associated with both light and heat and the slowest in the refrigerator, where light and heat were absent.

Children noted intermediate changes in locations where only one of these factors was present, and thus concluded that heat and light both made contributions to a tomato's ripening. These conclusions were supported not only by appeals to the current appearance of the tomatoes themselves, but by arguments based on the cumulative drawing records describing the tomatoes in each of the test locations. This shift exemplifies a further value of inscriptions in science—they preserve information in a format that permits reasoning within the constraints and world of the inscription alone, without the need to resort back to the fleeting events of the world itself.

Identifying and inscribing new attributes. By the end of the month, children had settled on a new word to describe the changes they were observing: “rot.” The odor was becoming noticeable, but children wanted to continue to observe change. They gathered their tomatoes and placed them in the school's courtyard for further observation. At this point, it was drawing close to Halloween, and the class moved on to a different seasonal theme, “pumpkin math.” Each child brought a pumpkin to class, and children wondered whose pumpkin was the biggest. This question provided another opportunity to consider how to problematize, clarify, and inscribe what at first seems self-evident. “Biggest” posed interesting questions about what was meant by “big”: Did it mean the pumpkin that was the biggest around? The tallest? The heaviest? Once again the children were faced with the problem of deciding attributes worthy of investigation. Reaching consensus about standards and units of measure occupied considerable debate. As children investigated whether pumpkin size was related to the number of its seeds, they had to reach consensus not only on how to measure size, but also on what would count as a seed (for example, what about the immature seeds)?

After exploring the mathematics of pumpkins, the children proceeded to carve them. Shortly thereafter, the telltale signs of rot once again became evident. Children drew upon their experience with tomatoes to predict what might happen with pumpkins. After further observation, they represented similarities and differences between pumpkin rot and tomato rot with the Venn diagram shown in Figure 1.

FIGURE 1. FIRST-GRADE OBSERVATIONS OF SIMILARITIES AND DIFFERENCES BETWEEN “TOMATO ROT” AND “PUMPKIN ROT”



Children expressed surprise at the comparative rates of change of tomato and pumpkin and asked about potential causes. Ms. Putz cut pieces of pumpkin and placed them into dishes for ease of observation. Children began to notice additional changes: “There are different kinds of molds.” Ms. Putz asked how they knew that, a question that led to further discussion about the relationships between the children’s observations and their inferences from the observations. The class generated an additional question: “How does mold happen?” The students pointed out that the change observable in the pumpkin dishes was a lot like what they were observing outdoors in their pile of tomatoes, although the rates of “rot” differed substantially. But, the children were concerned that with the approach of winter, their rot experiment would be arrested by the cold (or at least, hidden by the snow). At this point, Ms. Putz introduced compost columns as a model for the outdoor rot process.

The Inquiry Shifts: Modeling Rot

Filling two-liter plastic soda bottles with decomposing material, the teacher began by raising the question whether compost columns might serve as models for the outdoor system, asking, “Why couldn’t we just watch the pile that is already outside?” and “So what is it we are trying to do in our class with these columns?”

One child noted, “It is showing what something looks like,” and “You see how something is made and you make one yourself.” The emphasis in children’s responses on the idea of “looks like” reflects a more general orientation that we have noted among children toward thinking of models initially as representations that copy or resemble the phenomena being modeled (Penner et al., 1997). As one child proposed that a compost column was like a model airplane, Ms. Putz asked, “Look around the classroom. Are there other models?” Children considered globes and maps to be models, suggesting that some models resemble the world but still are not identical to it. “A globe isn’t the real same size or color, but it shows people what it looks like.” Returning to the compost column as a model, one boy suggested, “We want to watch what happens to the tomatoes until spring, but we want to do it in our room.”

Constructing models. Having come to convergence on the purpose of the compost columns, children proceeded to the problem of deciding which elements of the outdoor system should be replicated in the columns. Their choice was of objects that looked like the phenomena they had decided to track (rotting tomatoes outdoors in the dirt). Accordingly, they argued for inclusion of moldy tomatoes, dirt, leaves, gum wrappers, and a piece of foam. Once again, the teacher asked them to consider factors that might influence decomposition. Drawing upon their previous experience, children decided that one compost column would be kept warm and another cold (in the refrigerator). Other compost columns were constructed with pumpkin (to compare with those including tomato), and all were watered to mimic the effects of rain, which children felt would be important in the rotting process.

Children again observed change over time, drawing and noting what they observed: “I see mold, garbage, and leaves. The mold is white on the dirt.” Many children noticed the increasing amounts of mold in the columns. Ms. Putz asked, “Why do you think there is more mold?” Most children explained that there were a lot of dead things in the columns. They did, however, notice that compost columns kept in the room apparently had more mold than the column kept in the refrigerator.

Ms. Putz pressed further: “When we started to make the columns, both column A—the one in the room—and B—that in the refrigerator—had the same things. So why does column A have more mold in it than column B?” Children suggested, “Because of the cold.” When one child suggested that the mold might be growing, his remark was met with stunned silence. Ms. Putz reframed the conjecture: “Is the mold growing more in column A than in column B?” Most children objected that mold could not be alive. They seemed instead to associate mold with some unknown process connected with “dead things” and moderated (somehow) by cold. This notion that mold emanates from “dead things” is an example of a copy theory of generation that we sometimes observed: the belief, for example, that dead begets dead.

Attack of the fruit flies. In another compost column, one containing pumpkin, children noticed fruit flies, an observation prompting the question, “Where did the fruit flies come from?” A few children recalled that some of the pumpkins had worms, so they conjectured that the larvae had metamorphosed into fruit flies. Ms. Putz again pressed for evidence: “How do you know that the larvae turned into fruit flies?” Children returned to look at the column and were excited to find more larvae crawling around under some leaves. One boy noticed “bumps” on the wall of the container. “Ms. Putz, the larvae turn into bumps on the wall. Then they hatch into fruit flies! The fruit flies lay more eggs, and the eggs hatch more larvae!” Another boy added, “It’s like a circle story!”—a reference to a story the class had read about the life cycle of insects.

The next inquiry came from questions asked by children in other classrooms and their teachers, with varying degrees of asperity: “Where are these fruit flies coming from?” Yes, the fruit flies had escaped into the school. Noting that the complaints were coming from all over the school, children sent envoys to each classroom to count the number of flies observed during a brief visit. They then represented their observations on a map of the school, displaying different ranges of counts by coloring classrooms accordingly (classrooms with the highest counts of fruit flies were colored green on the map).

As they reviewed the completed map together, Ms. Putz asked, “Why are there three green classrooms in a row?” One child replied, “That’s easy, because they are next to our classroom, and our classroom has a lot of fruit flies.”

“Then why,” asked Ms. Putz, “are some of these classrooms in a different hallway green?”

A child excitedly replied, “I remember in all of those rooms the teachers said they saw the fruit flies around food places.” Other children explored the implications of this conjecture by reexamining their display and ultimately connecting

the higher and lower counts to what they knew about potential sources of food and water. The implications of these speculations about food and water sources were elicited again by Ms. Putz, who asked children to predict what might happen over time. Children suggested that when the food ran out, so too would the fruit flies. Subsequent observations confirmed this conjecture.

The fruit fly episode represents yet another important feature about inquiry, often brushed aside in the hustle of classroom schedules but valuable for helping children understand an important point about how scientific investigation proceeds. When things are cooking, either in the laboratory or in the elementary school classroom, investigations do not stop with the pursuit of isolated questions. Instead, they often stretch into a chain of inquiry from questions to investigation to new (and often more interesting) questions. Encouraging and helping children to extend that chain is something that excellent teachers like Ms. Putz do. This sends the important message that work conducted is not work completed. In these classrooms there is a continuing cycling of knowledge, questions, inscriptions, and data into new and more challenging next steps—the conceptual ante keeps rising, and children keep rising to meet it.

Is it alive? The children remained uncertain about the status of mold, so Ms. Putz decided to have them grow mold on wet bread. Using magnifying glasses and microscopes, the students observed change in greater detail. They viewed a “Magic School Bus” video about fungi, which served an important role in orienting them to the details of what to look for. Children noticed, for instance, that molds “...have stems like a plant and ball or a different shape on top for the flower or leaf part.” Analogies like these convinced children that the change in the volume of mold was due to growth, not to some unspecified abiotic process. To help children map from the bread mold to the mold in the compost columns, Ms. Putz asked a further question: “How is the mold able to live in our compost columns?” The children volunteered several factors: “Because it has food—leaf litter, tomato, pumpkin—and we have water in the columns. It would die if we stopped putting water in.”

As the character of the compost columns changed, the children’s inquiry continued to evolve. Many children wondered about changes in the volume of material and the disappearance of pumpkin and tomato. Students developed conjectures about the potential roles of mold and fruit flies in eating the food sources, and wondered whether the fruit flies themselves were then eventually dying and going into the soil. It was noted that some food sources decomposed more rapidly than others. Ms. Putz again raised the stakes by asking children for an explanation. The responses indicated that children associated more rapid

decomposition with observations of the actions of larvae and mold. Others noticed that the leaves were decomposing too, and Ms. Putz asked about their evidence for this claim. One girl explained, “When we first started, the leaves were crunchy and dry. Now they are wet, moldy, and smaller.”

When spring finally rolled around (a late event in this Northern state), children resumed observation of their outdoor tomato pile. Now, however, their inquiry and observations were informed by their experiences with the compost columns. Over the course of the year, children had come to regard science as a cycle of inquiry, observation, and inscription. Each step in the cycle built on the previous one, and each drew its meaning from the whole. The teacher’s questions introduced students to notions of conjecture and evidence, to considerations of models and modeling, and to the importance of comparison over time and among conditions. Although Ms. Putz certainly honored and worked with children’s natural curiosity, curiosity alone would not have taken the students very far. Instead, she worked systematically to design a classroom in which children engaged in progressive cycles of inquiry and evidence. Her design tools included questions that pushed her students’ questions further and acquainted them with norms of argumentation and evidence, the use of inscriptions and displays they devised, and evolving chains of inquiry. It was by refusing to rely on children’s curiosity alone that Ms. Putz fostered it.

UPPING THE ANTE IN THE LATER GRADES

Motivating and sustaining the curiosity of young children seems to be a matter of hooking to their interests and building on them, but many teachers wonder where and how to direct this enthusiasm when they work with students in the upper elementary grades, especially when the demands of the subject increase. At these ages we suggest, teachers are able to turn children’s reflection back upon their own inquiry, so that inquiry becomes more thoughtful and increasingly governed by a refined judgment about the questions worth pursuing. We also consider the advantages of helping students stretch their first inscriptions toward increasing mathematization. We are arguing not for letting science dissolve into computation, but for helping students develop a taste for the power of mathematical forms of argument.

Helping Students Pose Good Questions

One notable thing about Ms. Putz's teaching is how quick she is to pick up children's questions and push them forward in fruitful ways. Sometimes, especially in the later elementary grades, when teachers become primarily concerned that students acquire the knowledge and skills of a particular subject, they forget that genuine inquiry is rooted in questions. But how can children make meaning of an experiment or data collection that is not well anchored in a question that is real to the participants? The issue then on the table is: How does a teacher help students learn to pose good questions? In the older elementary grades, three through five, teachers will want to pay increasing attention to shifting students' attention beyond simply posing questions and toward reflecting about the potential and interest of the questions that are generated. Although many have encouraged teachers to welcome and listen carefully to children's questions and to let students discuss and investigate their own questions (Chaille & Britain, 1997; Gallas, 1995), little information is available to assist teachers at making these questions productive.

As Ms. Putz's experience shows, even the youngest students can generate a wide variety of questions about phenomena. But there are instructional practices that assist the process. We need to recognize that it takes time. Often, we rush right past question posing into data collection. Yet this is a time to slow down—explicitly opening up the process of generating questions and aiming toward the long-term goal of helping students develop criteria for what counts as a good question. Questions are generated readily when students work in groups, or when they can write a few questions individually and then contribute those to a group list. We find that students build on one another's ideas, especially if the teacher models appropriate criteria for evaluating questions as they are listed. One of our third graders, for example, asked of Wisconsin Fast Plants (a plant that completes its entire growth cycle within forty days), "How long will they grow?" The teacher asked which sense of "long" was intended. Was the student talking about size or time? The teacher also suggested the need to be sure we know to what "they" refers. As questions are generated and considered, the teacher will want increasingly to cede to the students themselves this process of evaluating questions.

Children generate more questions and more interesting questions when they are encouraged to build upon their own knowledge and experience about the phenomenon under investigation. Sometimes this means beginning with an extended conversation about what children know of a topic. Recall, for example,

how the first graders' initial knowledge about ripening helped them generate the comparison conditions for their tomato experiment. Shared experience in the classroom with an interesting event or organism serves as an excellent prompt for further questioning. As their knowledge of a phenomenon grows, children ask increasingly interesting questions. So sometimes it is wise to devote at least two phases to inquiry: one to gaining familiarity with the phenomenon of interest, and the second to more concentrated investigation. Most questions that one class of third graders generated before planting seeds to grow Wisconsin Fast Plants looked to endpoints of growth: "How tall will they grow?" A few concerned timing of events in the life cycle. During its second round of growing Fast Plants, however, the class generated more subtle questions. Some were oriented toward function such as the role of petals and pollen, others toward development: for instance, the typical shape of the growth curve. Interval—"On what day?"—raised issues. Still others involved comparison: for example, the effects of different amounts of fertilizer. Over cycles of inquiry, questions became increasingly elaborated: "how long does it take" gave way to "how many more days" and then to "what day." From "flower buds" to "role of petals" and "what makes pollen," questions grew more specific. They also reflected increasing cognizances of variation: the words "usually," "normally," and "mainly" begin to be used to qualify statements. Students also turned from queries about endpoints to questions about change over time and rates of growth.

One way to begin examining and evaluating questions is to record them on index cards and ask small groups to arrange and rearrange them into categories. Then each group of students describes its category system, a process that encourages children to read and become familiar with the range and variety of questions, as well as to consider additional ways of categorizing. We have observed similarities in the ways that students in the third grade through the fifth (and groups of teachers!) categorize questions. Some categorize by words that appear in the question; for example, all questions containing the word "flower" are grouped together. Others group by concepts. Questions about living organisms may be sorted into groups labeled, "growing," "size," or "environment." Some groups classify questions into the familiar format who-what-when-where-why-how. Occasionally, a student suggests that the questions be sorted by the type of answer expected. This insight often helps students understand that many questions that can be answered by a simple "yes" or "no" are less interesting than queries that call for more complex answers. Students may separate from problems that they think unsolvable others that can be addressed by authorities such as books and experts or by investigation. It can also be useful to ask the class

which questions are interesting or simple, and what makes them so. The class may consider which questions they could investigate within a given amount of time and which would take longer. Class discussions about how a question can be investigated are as important as later discussions about what has been learned from the investigation.

As students evaluate their questions, the teacher will also be considering which questions are most likely to be productive for extended class work. This will require attention to children's prior knowledge, the tasks and tools the question calls for, and the potential for developing reasoning and argument at both the planning stage and the resolution. Many hands-on science programs treat questions as givens, which invites students to regard science as the precise execution of prefabricated recipes of steps in pursuit of a solution to a question that nobody cares about. Time spent in helping students work at posing and revising questions also pays off in a deeper understanding of the results.

From Inscription to Mathematization

Recall that Ms. Putz's students' initial conjectures about whose pumpkin was biggest could not be answered definitively by merely inspecting the pumpkins. Instead, they had to achieve agreement about such attributes as height, width, and weight and about measurement: for young students, developing a firm understanding of measure is itself an accomplishment. In cases like these, children learn that their arguments and conclusions rest on firmer warrants if they can find ways to mathematize the world.

In another first-grade classroom, students explored the growth of flowering bulbs—amaryllis, hyacinth, and paperwhite narcissus. Although students could readily observe the bulbs growing, they required inscriptional resources to record, describe, and analyze the change. In addition to recording and drawing changes in their journals, students worked with cut out paper strips that preserved the height of each plant at each day of growth. The green color of the strips mapped easily onto the green of the stems. As is often the case with young students, these first graders found difficult the move from copy to representation. Eventually, however, they began to regard the strips not as copies of plants, but as representations of an attribute of the plants: height. The teacher assisted this move to representation by rearranging the strips in various ways to support conjectures raised by the children—for example, to compare the height of one plant as it grew and flowered, or to compare the height of different plants on the same day.

When the teacher introduced the question, “Which plant is growing fastest,” children initially selected the plant that was currently the tallest, and supported their argument by referring to the longest strip for each of the plants being compared. But one child pointed out that it wasn’t sufficient to refer just to the heights of individual strips; the class needed to consider differences in heights on successive days. On our segment of videotape, we can clearly see her considering the relevant height strips mounted side by side on a classroom chart. Using her thumb and forefinger, she marks off the successive differences from day to day so that the other students can see what she means when she talks about the difference. Children found this argument compelling, and went on to compare successive differences to answer the teacher’s question about two different conditions in which bulbs were grown. The students readily concluded that while the paper-white narcissus planted in soil had grown faster than the narcissus planted in water, eventually the bulb grown in water alone “caught up.”

Although the strips were first employed mainly in side-by-side eyeball comparisons, they eventually inspired more sophisticated questions about linear measure. Issues of measurement were first raised when an adjacent classroom asked, “Whose amaryllis is growing bigger, ours or yours?” Students tried to answer by holding up pencils alongside their growth strips and reporting back to the partner class that their amaryllis was “three pencils tall.” Then, a new question came back: “How big was your pencil?” The teachers found these conversations very fruitful for eliciting consideration of the need for standard units, iteration of units (with no spaces in between), and measuring from a common baseline, all important understandings for young children developing a theory of measure (Lehrer, Jenkins, & Osana, in press). Eventually, the children reinscribed the growth data in a table of measurements, and confirmed that the new data display could also be used to support their conjectures about endpoints, rates, and timing of growth.

Notice how closely intertwined in the first-graders’ work are questions, inscriptions, and argument. As children’s inscriptional resources became more sophisticated and mathematically powerful, the quality of their questions and arguments also expanded. Sustaining productive scientific reasoning requires going beyond exclusive reliance on observation and memory. Learning to describe events in ways that lend themselves to flexible and mobile forms of comparison is an important resource for moving classroom argument beyond appeals to what initially sticks in memory.

Similar issues come to the fore with older elementary students. In higher grades, however, teachers should be capitalizing on the increased leverage purchased by work in the earlier grades at developing children’s inscriptional and

mathematical resources, reflective criteria for evaluating their own inquiry processes, and internalization of mathematical and scientific argument.

A fifth-grade class's examination of insect growth for about six weeks was organized around a central question generated by the students: "Do [the larvae] grow better if they eat green pepper or 'recipe'?"—a standard formula developed by the University's Department of Entomology. As in the earlier grades, the class began by refining the question extensively. The students started with a discussion of the kinds and forms of data that could contribute to a satisfactory resolution. They eventually settled on rearing two groups of larvae, one fed exclusively on green pepper and the other fed on recipe. Students proposed that growing "better" might mean growing bigger or growing faster. As the investigation continued, additional senses of growing "better" were identified. Students pointed out that larval size and growth rate could be conceived by reference to length, width, height, or weight. Consensual procedures for finding values for each of these attributes were negotiated in the classroom. Several days into the experiment, a student proposed that growing "better" might mean "living longer," and this idea was also incorporated into data collection.

Their early data and observations led students to speculate that growth in length of larvae might be inversely related to growth in width and that larvae that grew faster and bigger might not live so long. This speculation contrasted with an earlier conjecture that growth rate and size would be directly related to mortality. These ideas were revisited later in light of data collected over the entire life cycle. Eventually, students compared growth rates for several attributes and debated which would count as growing better.

Toward the close of the unit, students developed frequency and line graphs to develop and justify conclusions about the growth of the two groups of larvae. These mathematical representations, in turn, inspired several new conceptions of growing better. One student proposed that larvae showing normal or typical growth might be growing better than one that was simply large, partly because larger organisms might be more susceptible to predation. Another student pointed out that the larvae feeding on green pepper lived longer in the caterpillar stage than the ones fed with recipe, which survived to pupate and eventually emerged as adults. This idea was extended by a student who thought that another sense of living longer (and hence "growing better") would include larvae that grew large over a longer time than others took.

A central point is that during their repeated reflections about their data displays, many of the most interesting questions students posed were inspired not by direct observation of the organisms, but by the emerging qualities of the displays

themselves. Increasingly, these qualities included important mathematical ideas. Students inspected one chart displaying a bivariate frequency plot comparing the effect of recipe with that of pepper on body length of the larvae on different days of growth. They noted that the display showed not only differences between the two treatment groups in typical body length but also that the larvae fed recipe showed greater variability in body length. As one student put it, “The recipe got kind of spread out, and they’re not really bunched up.... Green pepper doesn’t really spread out much.” Students speculated about possible causes of the discrepancies. Did it matter, for example, that the insects fed recipe tended to grow faster and therefore may have been moved to a larger container more quickly than the others? These conjectures, in turn, led to discussion about how the original experiment might be redesigned to eliminate possible confounds. This kind of repeated cycling between data and explanation, working to identify ways that each can illuminate the other and to seek alignment between them, is typical of the kind of scientific argumentation conducted by practicing scientists.

CONCLUSION

We might conclude that elementary school students are like child scientists because our experiences and those of others suggest that reasoning about the natural world can be provoked by inquiry not too far removed from children’s curiosity and play. Sustaining and elaborating these initial efforts, however, requires attention to some important design features that are seldom articulated, features that teachers can orchestrate to help children build a chain of inquiry rather than a succession of fleeting interests.

Like scientists, students work most productively when in communities that embody and inculcate norms about interesting inquiry, good explanation, and argumentation based on evidence. Teachers like Angie Putz initiate and sustain chains of inquiry about the natural world by calling children’s attention to events—what happens to apples; by questions that prompt consideration of explanation and evidence; and by efforts to help children reflect upon the history of their inquiry: comparing “How we used to think,” for example, with “How we think now.” Inquiry is not regarded primarily as exploration and experiment, in which the meaning of investigation is assumed to be self-evident. The work centers instead in argument and explanation, the negotiated and constructed nature of meaning and evidence. That approach is consistent with recommendations in the *National Science Education Standards* issued by the National Research Council in 1996.

Children, like scientists, mediate their inquiry by tools, inscriptions, and notations. Although we certainly want children eventually to understand the powerful symbols and tools of scientific practice, the treading here must be light. It is usually a mistake to give children solutions too soon to problems that they have not yet experienced as problems. Although one can simply teach children accepted procedures for collecting and representing data, we find it much more powerful to build from the inscriptions and displays that children invent on their own in the process of pursuing questions that they have helped pose and refine. This involves students themselves in considering what properties the display should feature. Even more important is that they are brought into the evaluation process that occurs when the first attempt is completed: Does the first try at a graph or drawing or diagram clearly communicate to someone who wasn't part of the data collection team? Does it really throw any light on the original question? Almost always, revisions are required, and students learn the important lesson that inscriptions need to be revised and retuned to the purposes at hand. They also understand that the tools of science were invented for a purpose.

Questions, inscriptions, and argument go hand in hand. Growth in one almost always leads to growth in the others. Yet in our experience, this kind of development does not spontaneously emerge. Representational displays and arguments are important for framing questions in fruitful ways, for answering them, and for provoking new questions that emerge out of the qualities of the inscription. In effective inquiry, teachers work to help students develop consensual criteria for what counts as a convincing argument and an interesting question. Learning to master the interplay between question, inscription, and argument puts students on the road to becoming authors of scientific knowledge. It is in making students authors of knowledge rather than mere consumers that it is valuable to have them inquire about the growth of *amaryllis*, the spread of fruit flies, and the decomposition of tomatoes.

ENDNOTE

1. Correspondence concerning this article should be addressed to any of the authors at: Department of Educational Psychology, 1025 West Johnson, Madison, WI 53706. This research was supported by the James S. McDonnell Foundation's Cognitive Studies in Educational Practice Program and by the National Center for Improving Student Learning and Achievement in Mathematics and Science (NCISLA), which is administered by the Wisconsin Center for Education

Research, School of Education, University of Wisconsin-Madison. NCISLA is funded by the Educational Research and Development Centers Program, PR/Award number R305A60007, as administered by the Office of Educational Research and Improvement, U.S. Department of Education. The contents do not necessarily represent the position or policies of the funding agencies. We are grateful to the participating teachers and students and to other contributing research staff and students.

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Ways of Fostering Teachers' Inquiries into Science Learning and Teaching¹

Emily H. van Zee

What does it mean to use inquiry approaches to learning and teaching? How do teachers who teach this way think about what they do? One way to find out is for researchers to study how such teachers teach. Another way is for the teachers themselves to study their own practices and to communicate their findings. This chapter reviews some of the relevant literature and then describes my efforts to foster such research.

WHY WOULD TEACHERS CHOOSE TO INQUIRE INTO THEIR OWN TEACHING PRACTICES?

Teachers typically have little time, resources, or encouragement to undertake inquiries into their own teaching practices. Why would they choose to do this? In *Teaching as Research*, Eleanor Duckworth articulates a vision of conducting research as an integral part of teaching:

I am not proposing that school teachers single-handedly become published researchers in the development of human learning. Rather, I am proposing that teaching, understood as engaging learners in phenomena

and working to understand the sense they are making, might be the *sine qua non* of such research.

This kind of researcher would be a teacher in the sense of caring about some part of the world and how it works enough to want to make it accessible to others; he or she would be fascinated by the questions of how to engage people in it and how people make sense of it; would have time and resources to pursue these questions to the depth of his or her interest, to write what he or she learned, and to contribute to the theoretical and pedagogical discussions on the nature and development of human learning.

And then, I wonder—why should this be a separate research profession? There is no reason I can think of not to rearrange the resources available for education so that this description defines the job of a public school teacher. (1987, p. 168)

Through such inquiries, teachers can document the details of their students' thinking, deepen their own understanding of both science content and pedagogy, share their insights with colleagues, and contribute to knowledge about learning and teaching.

In *Doing What Scientists Do: Children Learn to Investigate Their World*, Ellen Doris provides many examples of teaching as researching. She writes:

We can, in effect, work as researchers in the classroom, observing children carefully, listening to what they say, noting when our responses seem to baffle them and when we help them to take a step forward. Science textbooks may offer us information to present or questions to raise, but only our careful attention to children will enable us to gather information about what they find interesting or puzzling, which ideas they understand and which ones confuse them. (1991, p. 11)

Doris shares insights and experiences by interpreting transcripts of conversations in her classroom, commenting about her students' drawings and writings, and telling stories about what happened as they explored together.

“Conducting formal and informal classroom-based research is a powerful means to improve practice,” according to the National Research Council (NRC) in the *National Science Education Standards* (p.70). Listening closely to what students say, for example, can help teachers become more expert in diagnosing student thinking and in modifying instruction accordingly. A shift in emphasis from “teacher as consumer of knowledge about teaching” to “teacher as producer of

knowledge about teaching” is desirable in designing in-service activities for teachers (p. 72). Professional Development Standard D states:

Professional development for teachers of science requires building understanding and ability for lifelong learning. Professional development activities must...provide opportunities to learn and use the skills of research to generate new knowledge about science and the teaching and learning of science. (NRC, 1996, p. 68)

The premise is that teachers may find discussing data they have collected in their own classrooms more interesting and directly helpful than in-service sessions in which they hear experts talk about applying the results of formal research to teaching.

Teachers' inquiries also may yield insights and information that outside researchers would not be able to access or generate. The potential for teachers' inquiries to inform and reform educational practices motivated an initiative by the Spencer Foundation. In 1996, the Foundation launched a program to support research on ways to increase communication and mentoring among practitioner researchers because:

...research conducted in school sites by educational practitioners may offer specific and useful knowledge about education which can best be, perhaps only be, generated out of the experience of the practitioner. (1996, p. 32)

Funding can provide support for regular substitutes who engage students in on-going and coherent instructional experiences while the teachers work on their research. Such support can also enable teachers to present at conferences and to devote summers to analysis and writing.

Interest in teachers' accounts of their practices is not new. More than half a century ago, John Dewey recognized the potential of teachers to contribute to knowledge about teaching:

This factor of reports and records does not exhaust, by any means, the role of practitioners in building up a scientific content in educational activity. A constant flow of less formal reports on special school affairs and results is needed.... It seems to me that the contributions that might come from classroom teachers are a comparatively neglected field; or, to change the metaphor, an almost unworked mine. (Wallace, 1997, pp. 26-27)

In particular, Dewey advocated such inquiries in progressive schools that emphasized self-initiated and self-conducted learning:

The method of the teacher...becomes a matter of finding the conditions which call out self-educative activity, or learning, and of cooperating with the activities of the pupils so that they have learning as their consequence ...A series of constantly multiplying careful reports on conditions which experience has shown in actual cases to be favorable or unfavorable to learning would revolutionize the whole subject of method. (pp. 125-126)

Developing such case studies of student learning is a way that teachers can contribute to the knowledge base for improving instruction.

WHAT DO TEACHERS INQUIRE ABOUT THEIR OWN TEACHING PRACTICES?

Many teachers feel uneasy when first formulating research questions, particularly if they think of research as involving the treatment and control groups typical of traditional studies. “What are you curious about in your classroom?” may not seem appropriate. Most teacher research is interpretative, however; both the questions and the analyses evolve throughout the research process. In a preface to a special issue of *Teacher Research: The Journal of Classroom Inquiry*, the editors describe the beginning of such inquiries:

It might be a question that darts into your mind and you take the time to ponder it, rather than brushing it aside with an “I’m too busy to think about it now” shrug. Or it might be your decision to look a little more closely at that kid who is driving you crazy in class and keeping you awake at night. It could be the first time you put pen to paper in a teaching journal, press the record button on a tape recorder, or sit down to talk with a teaching colleague about something you wonder about. But it begins somewhere. (1998, p. v)

In addition to papers by both beginning and experienced teachers, this journal includes a tool box section in which teacher researchers describe some of their research methods.

Some teachers have documented and interpreted changes that were occurring in their schools. Such studies are appropriate for publication in *Teaching and Change*, a publication of the National Education Association:

Teaching and Change provides an open forum for reporting the experiences of classroom teachers as they learn how schools must change to make good practice possible. The journal is devoted to helping teachers as they work to strengthen their learning communities. Issues discussed in *Teaching and Change* include what is taught, how it is taught, and the different ways schools are organized. (1997)

Articles in this journal have traced the results of changes in classroom practice, examined ways of teaching particular processes, explored the effects of program restructuring, and investigated development of student understandings.

Sometimes teachers get started by participating in study groups in collaboration with an university researcher. In a chapter of a book co-edited by such a group, for example, Charles Pearce reported his thinking at the beginning of a research project:

What if, I thought while driving home that day, I tried giving fifth-grade students boxes of materials with no directions, no packets of activity cards? There would be no hidden agendas, no regimented steps to follow, no expected outcomes. Would learning take place? Could that learning be assessed? Would this approach engender higher-level thinking and enable the students to monitor and evaluate thinking processes? Could the curriculum still be addressed if students were afforded a wide range of choices? What if.... (1993, pp. 53-54)

Pearce's chapter includes many examples of student work, such as questions students wrote on a Question Board, a student's entries on a Know, Wonder, Learn form for an activity on mealworms, a completed discovery log for a crayfish activity, a sign-up list for an inquiry period, a completed inquiry period log sheet, a completed tower workshop log sheet, several examples of completed "What I Accomplished" forms, the first page of a class Body of Knowledge booklet, and a story written by a student. Pearce's inquiries eventually developed into a book of his own published in 1999, *Nurturing Inquiry: Real Science for the Elementary Classroom*, in which he presents and discusses a wide variety of data from his students' explorations.

Teachers can gain information and inspiration from the work of their colleagues. Barbara Bourne, for example, reports an outgrowth of Pearce's "What If"

thinking in a chapter in a second book by their teacher-researcher group, *Beyond the Science Kit: Inquiry in Action*, published in 1996. Bourne's chapter describes her students' experiences at a Kids' Inquiry Conference during which they shared findings from their investigations of topics of mutual interest. Reading this chapter inspired a fourth-grade teacher, Diantha Lay, to consider ways to shift from competitive science fairs to more collaborative contexts at her school. She discusses her experiences in her contribution to the collection here.

Some teachers have written books that focus upon particular aspects of their practices. Karen Gallas describes her inquiries, for example, in *Talking Their Way into Science: Hearing Children's Questions and Theories, Responding with Curriculum*:

This book is about science. But it is also about a question. It is intended to be a very focused look at one aspect of science teaching and learning: Talk. Within the realm of talk, it focuses on a very particular kind of talk—that is, dialogue among children.... What I will describe in this book is how our practice of Science Talks developed in my primary classroom in response to my own question as a teacher researcher. My reflections will focus alternatively on what “real” science is, on the study of science in schools, on children as thinkers, on the role of theory in the science classroom, on the nature of collaboration and discussion, on different kinds of talk, on the acquisition of a discourse, on the teacher's role in science instruction, and on the social construction of learning. In this process, I will necessarily share the details of some of my work as a teacher researcher, and those details also will illuminate the ways in which the act of teaching and learning evolved in my classroom. (1995, p. 1)

Gallas' book includes many examples of students talking with one another and their teacher, along with complete transcripts of two talks in the Appendix. Gallas espouses many of the values that a university researcher, Jay Lemke, stressed in his study, *Talking Science: Language, Learning, and Values*, but she discusses these from the perspective of a teacher who is sharing with other teachers a deep knowledge of what has worked well for her, how, and why.

HOW DO TEACHERS INQUIRE INTO THEIR OWN TEACHING PRACTICES?

Many teachers collect data as part of their usual ways of doing things, such as writing down their thoughts about a lesson and ways they might make changes next time. In reflecting upon her work, Peggy Groves comments upon the additional demands of research:

The difference between my recent classroom research and my usual classroom practices is that for my research I kept notes about what I did, I looked more closely at what happened, I asked myself harder questions, and I wrote about it all. These differences took a lot of time, but I think I'm a better teacher for it. And maybe even a better writer. (Hubbard & Power, 1993, p. xv)

Such reflective writing can help develop questions that can guide further explorations. Talking with colleagues also can be useful. In an article about collaborative action research, for example, Allen Feldman (1996) describes ways in which a group of physics teachers generated and shared knowledge that enhanced their normal practices.

Systematic inquiries require time, resources, and a collegial milieu. The support of school administrators is critical. The *National Science Education Standards* articulated the kind of school support necessary:

Program Standard F: Schools must work as communities that encourage, support, and sustain teachers as they implement an effective science program.... Schedules must be realigned, time provided, and human resources deployed such that teachers can come together regularly to discuss individual student learning needs and to reflect and conduct research on practice.... Time must be available for teachers to observe other classrooms, team teach, use external resources, attend conferences, and hold meetings during the school day.... For teachers to study their own teaching and their students' learning effectively and work constructively with their colleagues, they need tangible and moral support.... As communities of learners, schools should make available to teachers professional journals, books, and technologies that will help them advance their knowledge. These same materials support teachers as they use research and reflection to improve their teaching. (NRC, 1996, pp. 222-223)

Such standards can provide guidelines for both teachers and administrators who choose to initiate teacher researcher programs.

Extensive teacher researcher programs may include school-based study groups, district-wide seminars, newsletters, and conferences. Teachers in Fairfax County, Virginia, for example, initiated a teacher research network that publishes a quarterly newsletter, *The Networker*, and mounts an annual Teacher Research Conference where teachers can present their work.

One of the first books to provide guidance for teacher researchers was published in 1993, *Inside/Outside: Teacher Research and Knowledge* by Marilyn Cochran-Smith and Susan Lytle. Others include *Research and the Teacher: A Qualitative Introduction to School-Based Research* by Graham Hitchcock and David Hughes. The editors of the journal *Teacher Research*, Ruth Hubbard and Brenda Miller Power, have published two guides, *The Art of Classroom Inquiry* in 1993 and *Living the Questions: A Guide for Teacher Researchers* in 1999. The latter includes research strategies illustrated with examples, guidelines for setting up school-wide inquiry groups, ethical considerations, and advice from veteran teacher researchers on many topics.

Angelo Collins and Samuel Spiegel (1997) provide advice on doing action research as part of a collection of science teachers' studies in *Action Research: Perspectives from Teachers' Classrooms*. In *Probing Understanding*, Richard White and Richard Gunstone (1992) describe many techniques that teachers can use to diagnose their students' thinking. These include asking students to represent connections among ideas with a concept map or list of word associations; inviting students to justify predictions and then to reconcile their predictions with observations; interviewing students about instances, events, or concepts; interpreting students' drawings, line graphs, or relational diagrams; and assessing questions students produce in response to various prompts.

HOW CAN PROSPECTIVE TEACHERS LEARN HOW TO DO RESEARCH WHILE THEY LEARN TO TEACH?

As a new instructor of courses on methods of teaching science in elementary school (1998b), I wanted to prepare prospective teachers to do research as well as to teach. My vision of teachers as researchers reflects my experiences collaborating with the co-editor of this volume, Jim Minstrell, in trying to understand how he used questioning to guide student thinking (1997a,b). Minstrell (1989) had established a research site in his high school physics classroom where he, his students, several colleagues, and university researchers such as

myself all collaborated on studies of learning and teaching. I also drew upon my experiences in collaborating with teachers on an investigation of questioning during conversations about science (van Zee et al., in press). In interpreting dialogue, we used methods derived from my graduate studies with an ethnographer of communication, Gerry Philipsen (1982, 1992). The collection here includes case studies of questioning developed by two primary teachers, Marletta Iwasyk and Akiko Kurose, an upper elementary school teacher, Judy Wild, and a high school physics teacher, Dorothy Simpson. I had met these teachers while assisting in physics programs at the University of Washington (McDermott, 1996).

My approach to teaching science teaching is similar to that of instructors such as Sandra Abell and Lynn Bryan (1997) who emphasize reflective practices. Like Cronin-Jones (1991), I use interpretive research methods in teaching teachers. Many of these are similar to ways that George Posner (1985) recommended to student teachers for reflecting upon their field experiences. Activities and assignments in my course include a joint analysis of factors that foster science learning, development of a personal framework for science teaching, a sustained inquiry into a natural phenomenon, research on learning and teaching, and formulation of a research question for the final.

Joint Analysis of Factors That Foster Science Learning

The prospective teachers begin learning to do research at the beginning of my course on methods of teaching science in elementary school. The opening activity is an example of eliciting experiences from a variety of individuals and identifying common themes. I ask the prospective teachers to think about experiences inside or outside of school in which they have enjoyed learning science. They draw pictures of these experiences, write captions, and identify factors that fostered their learning in these instances. Then members of each group make a poster with their drawings and jointly construct a list of factors that fostered science learning across their experiences. They introduce themselves to the class by showing their poster, describing their experiences, and stating the factors they identified. Then we construct a list of factors common to all the groups.

On the first day of the fall 1998 class, for example, one of the prospective teachers drew a picture of herself moving in front of a computer connected to a motion detector. She and her classmates constructed the following list of factors that foster science learning: hands-on, relating to real life, interesting and fun, different environments, working in groups, a sense of anticipation, trial and error,

creativity, asking and answering questions, student-centered, self-discovery, curiosity. These were a good match to aspects of the teaching standards advocated in the *National Science Education Standards* (1996) but emerged from the prospective teachers' own analyses of their positive experiences in learning science. Although many thought they had not heard the phrase "inquiry approaches to teaching and learning" before, I interpret these findings to mean that these prospective teachers were entering my course with substantial prior knowledge on which to build.

When I asked the prospective teachers to raise their hands if the factors they had identified were typical of their science learning experiences, however, few hands went up. The positive experiences they had remembered and drawn had been unusual. Few seemed to remember studying much science of any kind in elementary school. Most had had negative experiences in high school and college science classes. We interpreted the results of this informal survey as evidence for the need for reform.

Development of a Personal Framework for Science Teaching

Throughout the semester, the prospective teachers continue reflecting upon factors that foster science learning. They write weekly journals that first describe science learning events they observe or experience themselves and then reflect upon factors that fostered science learning in these instances. One of them wrote a journal, for example, in which she described in more detail her experiences in the physics course that she had remembered on the first day of class:

In our science methods class, I drew a picture of a science learning process where I was involved as a student. Last semester, I took a class called Physics for Elementary School Teachers. The class was taught dramatically different than any other science class I've taken. We designed our own experiments and created our own formulas. The constants in the formulas were values that were results of experiments we did in class. We also formulated our own definitions for scientific terms. (This can be harder than it sounds.) It was common knowledge that the professor and teaching assistants were not the sources of answers. If we asked a question, they would answer it with a question. If an experiment was necessary to answer the question, they would point us to the materials. One of my favorite experiences was one that my partner and I designed...(describes experiment). The

most important part of this experiment was not the value of the initial temperature of liquid nitrogen. It was that we were able to design our own experiment and solve for the temperature using an equation we created. The class equipped us with a confidence in science that motivated us to persist until we found the answer. (First reflective journal, Spring 1998; emphasis added on the last day of class)

Thus week by week, the prospective teachers continue to reflect upon science learning in progress. At the end of the semester, they analyze these self-generated data for common themes and then use these themes to build personal frameworks for science teaching and learning. The prospective teacher who wrote the journal above, for example, underlined sentences in which she had stated factors that fostered learning, cut these out, and sorted them into a pile along with similar statements from later journals. These she taped together on a sheet of paper and wrote a summary statement at the top: "Students should learn to develop their own questions and design experiments to answer those questions." For the final, she used this and other themes to articulate recommendations for science teaching. For example, she wrote "Teachers should model scientific inquiry by encouraging students to develop their own questions and design experiments to answer their questions. This will increase the students confidence in science." As part of the final, the prospective teachers also present a lesson on a topic of their choice and describe how they would meet their recommendations in this context. Through this process, they have used a research technique to develop and elaborate their own principles for action as science teachers.

Sustained Inquiry

We also engage in a sustained inquiry about a natural phenomenon, the changing phases of the moon, in a manner similar to that described by Eleanor Duckworth (1987). I draw on *Where is the Moon?*, developed for students by *Elementary Science Study* (1966), and the astronomy section of *Physics by Inquiry*, developed for teachers by Lillian McDermott and the Physics Education Group at the University of Washington (1996).

At the beginning of the semester, the prospective teachers record their current knowledge about the moon, the nature of scientific explanations, and inquiry approaches to learning and teaching. Their assignment is to look at the sky daily, enjoy what they see, and record their observations if they see the moon. If they

cannot see the moon, they record that too. In class, they share their observations with one another and generate questions to guide further observation. Eventually we go outside on a sunny day when the moon is visible and hold up balls so that the lit portion of the ball matches the shape of the lit portion of the moon. The prospective teachers move the balls so that the pattern of the changing shape of the lit portion of the ball matches the pattern of the changing phases of the moon that they have observed. We move inside to work with a bright light, ping pong balls, and themselves to model the sun, moon, and Earth. They then write papers that present their observations, articulate the explanatory model we developed in class, and reflect upon changes in their understandings of the phases of the moon, of the nature of scientific explanations, and of inquiry learning and teaching.

In reflecting upon this sustained inquiry about the phases of the moon, a prospective teacher wrote:

I can now see that our moon project was specifically designed to model this for us. We students were active participants in the shaping of our own learning. Sure, we were directed to observe the moon on a daily basis, but at the same time we were allowed the freedom to interpret our findings in a way that made sense to us. I know that I personally, came up with many “whys” and “why nots” along the way and that this only served to further motivate me in ways that I never thought possible. Because of these questions that kept popping up as a result of my ongoing observations, I was excited to observe even further to find all of the answers. I think that this is what the “inquiry approach to learning and teaching” is all about. It’s almost as if a sense of curiosity is aroused in the individual that can only be satisfied through further inquiry. It kind of builds upon itself. I for one enjoyed the whole experience and plan to take this approach with my own students some day!

My conviction is that prospective teachers need such experiences themselves in order to envision the approaches to science teaching and learning that I advocate in the course.

Research on Learning and Teaching

The major assignment for the semester is a research project that each prospective teacher conducts in the placement setting. They all are placed in schools with diverse populations of students, many from low-income immigrant families. The

project involves exploring resources for teaching science in this setting, consulting with the mentor teacher to identify a science topic to teach later in the semester, examining ways various curricula present the topic, identifying relevant children's literature and technology resources, interviewing children to hear how they think about the topic before instruction, and designing a conversation about the topic. I use the phrase "conversation about science" to refer to the lesson in order to emphasize the importance of engaging students in discussing what they think. I use the term "design" because I require more than the usual components of a lesson plan. A design for a conversation about science also includes specifying questions to elicit student thinking, discussing accommodations for children with special needs, indicating ways to integrate across the disciplines, and making connections to district, state, and national standards. Each of the prospective teachers also formulates a research question to explore in this context. Before teaching and researching in their placement settings, the prospective teachers prepare by teaching and researching with peers in class. They collect data such as tape recordings of their lessons, copies of students' work, journal reflections, etc. The final product is a reflection about what happened both in the teaching and the researching.

Formulation of a Research Question for the Final

For the final, the prospective teachers write about ways in which they would teach lessons of their choice to meet the recommendations they developed as part of their personal framework for science teaching. They also formulate research questions that they can examine during their student teaching. Trisha Kagey, for example, elaborated her initial question:

The Role of Science Journals in a Science Inquiry Classroom

I want to explore the role of science journals in a science inquiry classroom. I believe that science should be integrated with other content areas, including language arts. Writing and drawing are methods of expression and communication. I am curious as to how students communicate their observations and results from investigations in their science journals. I also want to explore how science journals can be involved in the questioning, designing, experimenting, and communicating phases of scientific inquiry. I plan to discover the teacher's role in encouraging thoughtful responses in scientific journals.

My hope is that formulating a research question for the final will encourage prospective teachers to focus on an issue that interests them during their student teaching. Kagey, for example, was able to present her work in progress the following semester at a research festival that I had organized. She was able to continue her research during student teaching because of her placement with an earlier graduate of my course, Deborah Roberts. We are attempting to create a community of teacher researchers so that student teachers can be mentored in researching as well as teaching during their student teaching semester.

HOW CAN BEGINNING TEACHERS BUILD THEIR EXPERTISE IN RESEARCHING AS WELL AS IN TEACHING?

Forming or joining a teacher-researcher group can provide support for teachers interested in inquiring into their own teaching practices. The Science Inquiry Group (SING), for example, includes student teachers, beginning teachers, experienced teachers, and myself, a university instructor. With funding from the Spencer Foundation Program for Practitioner Research, we have been meeting monthly after school to share experiences and insights about science learning and teaching (van Zee, 1998a). Initially we met as one group in a participant's classroom. This year the original group is meeting at a more central location, in a local library, and a new group has formed within a participant's school. An on-site group has many advantages such as sharing equipment, ideas, and encouraging words on an on-going basis.

SING participants are developing case studies of science learning and teaching. We try to focus upon positive aspects of our practices: What are we doing that is working well, about which we might collect some data as we teach in order to understand better what is happening, so that we can communicate these successes to our colleagues? This paper, for example, is a case study of what I do as an instructor of courses on methods of teaching science and as the initiator and facilitator of a teacher researcher group.

Our case studies evolve through a complex process. We have found that a good way to start is to write an abstract. We prepare these abstracts for Research Festivals in which the teachers discuss their ongoing research with prospective teachers enrolled in my courses on methods of teaching science. Writing abstracts, collecting some data, and engaging prospective teachers in discussing these data seems to be a good way to begin making progress and to build self-confidence in doing research.

Some members of the group are interested in going to conferences and presenting their work in more formal settings. Presentations at the Research Festivals form the basis for writing proposals to do so. The Research Festivals also serve as rehearsals for our conference presentations. Typically we propose individual papers to be presented together in a group session. We begin by having presenters briefly introduce their case studies; then we divide into small groups so that the presenters can discuss their research in a non-threatening environment with a lot of interaction with participants in the session; we close with a whole group discussion based upon issues that have emerged in conversations within the small groups. Presenters usually hand out copies of their case studies as works in progress. Further refinement occurs as those interested prepare their case studies for publication. An example is "The Sky's the Limit: Parents and First-grade Students Watch the Sky" by Deborah Roberts (1999) published in *Science and Children*.

HOW CAN UNIVERSITY FACULTY FOSTER INTERACTIONS AMONG PROSPECTIVE AND PRACTICING TEACHER RESEARCHERS?

One of the most important opportunities that the Science Inquiry Group (SING) provides is for interaction among prospective and practicing teacher researchers. At the beginning of each semester, the SING teachers present their case studies at the Research Festival that we hold jointly with my course on methods of teaching science in elementary school. This enables me to put the undergraduates in direct contact with practicing teacher researchers. We meet after school in the classroom of a graduate of my fall 1995 class who is now a third-year teacher. At the spring 1999 Research Festival, presenters included an undergraduate student teacher, two first-year teachers, and several earlier graduates of my course as well as some experienced teachers. The graduates were able to show how the research questions that they had formulated in my courses have evolved into their current projects.

After the SING teachers discuss their own research, each helps a small group of the undergraduates plan a lesson to conduct in the SING teacher's classroom and also to formulate a research question to examine in this context. Each small group of undergraduates then visits their SING teacher's classroom to observe this teacher in action and to complete their collaborative planning. Next they try out their teaching and researching with peers in my class at the university. After doing the same with children in the SING classrooms, the small groups use my next class to reflect upon their experiences by developing posters that report their findings. The following class is again a joint meeting with the Science

Inquiry Group at which they discuss with the SING teachers their teaching and researching experiences in these classrooms. I intend this complex process to provide hands-on experiences in teaching through inquiry, in authentic contexts, in collaboration with practicing teachers who teach science this way, with opportunities to formulate and explore the prospective teachers' own questions about science teaching and learning. In other words, I am attempting to teach science teaching through inquiry.

This process requires five class sessions and two monthly meetings of the Science Inquiry Group. An evaluation of this process at the close of the Spring 1999 joint meeting indicated that both groups seemed to value this investment. The prospective teachers were pleased to have experience teaching in a realistic setting. One wrote, for example, "It was REAL!! We were working with students. This is much better than any lesson we could learn sitting and watching a teacher." They also appreciated the opportunity to observe and practice inquiry-based teaching. One commented, "As for the inquiry lesson, I learned a great deal. The children were active learners; this stuff really worked! I was really happy after teaching the lesson; I had this feeling of accomplishment." In addition, they enjoyed meeting with Science Inquiry Group teachers and talking with them about teaching and researching. One noted, "The SING meetings themselves were extremely valuable. I thoroughly enjoyed hearing the ideas and views of practicing SING teachers, as well as their input on what we are doing."

The prospective teachers also gained confidence in themselves and in teaching science. One wrote, "I really learned a lot from both the students and my colleagues but also from myself. This was the first time I ever stood in front of fourth graders. I was really surprised and pleased by my own confidence and performance." Another wrote, "I learned that I don't need to know everything about science in order to teach it. The students will come up with their own wonderful ideas as long as I facilitate and ask questions to keep them thinking." Several commented on the importance of having an opportunity to exchange ideas and views with others. One noted, "We worked in groups which exposed us to new ideas and views." Some indicated they had experienced a change in attitude toward science. One commented, "The investment of five class periods was very worthwhile and my experience in a science classroom has changed to very positive (since I wasn't very enthusiastic about science before)."

The Science Inquiry Group teachers felt they too had learned from the process. One of the SING teachers, for example, wrote about her experiences with the prospective teachers, "They continue to "stretch" me and force me to reflect on what I am doing. It gives me a chance to observe/critique their

teaching, which is helpful in critiquing myself.” One mentioned that the children also had gained by having guest teachers teach them a lesson.

ENDNOTE

1. The development of this manuscript was supported in part by a grant from the Spencer Foundation Practitioner Research: Mentoring and Communication Program. The data presented, statements made, and views expressed are solely the responsibility of the author. An earlier version of this paper was presented at the 20th Annual Ethnography in Education Research Forum at the University of Pennsylvania, Philadelphia in March 1999 under the title “Facilitating Reflective Research in School Settings: The Science Inquiry Group.”

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Learning to Teach Science Through Inquiry: A New Teacher's Story¹

Deborah L. Roberts

My undergraduate courses introduced me to learning through inquiry and doing teacher research. That was the beginning of a journey I am still enjoying as a third-year teacher. The road is not always direct, the questions often change, but the learning is fulfilling, enlightening, and fun!

LEARNING TO INQUIRE

My first experience in learning through inquiry was in an undergraduate physics course for future elementary and middle school teachers taught by Dr. John Layman. Dr. Layman is an expert in inquiry teaching (Layman, Ochoa, & Heikkinen, 1996; National Research Council [NRC], 1996). In this class I learned a lot about physics, but I also learned that it can be exciting to learn! I vowed during this class that this was the method of teaching I would try to model in my future classroom.

My first experience in doing teacher research was in a course on methods of teaching science that was taught by Dr. Emily van Zee (1998b). As described elsewhere in this collection, she required weekly observations of “science learning in progress” in our placement classrooms or in our personal experience. The

culminating assignment involved rereading all of our entries and looking for commonalities. We each came up with an individual list of the recurring themes in our observations. The last day of class, we shared these themes. I discovered four common themes among all of our lists: science learning needs to be hands on; science learning needs to follow the natural curiosities of the children; science learning needs to make real-world connections for children; and there needs to be a dedicated caring teacher who is able and willing to develop a sense of community in the classroom so that risk-taking will occur.

This discovery of what I considered to be the four essential conditions to foster science learning shaped my philosophy of teaching. All of these conditions had been evident in my physics class and my science teaching methods class. These discoveries also enabled me to do my student teaching according to my philosophy and to withstand criticism from my cooperating teacher and teaching supervisor, neither of whom appeared to have an understanding of inquiry teaching.

HELPING TO FORM A RESEARCH COMMUNITY: THE SCIENCE INQUIRY GROUP

During my first year of teaching, I helped form a group of teachers who were interested in doing reflective research in collaboration with Dr. van Zee (1998a). This version of teacher research differs from action research in its focus on positive aspects of the teachers' practices. The purpose of collecting data is to communicate to others what is working well rather than to guide actions for improving problematic situations. We call ourselves the Science Inquiry Group or SING. Among our goals are building our capacities to do research, communicating our findings to others, and supporting one another in our efforts to do research. We meet once a month after school to share our experiences and ideas about teaching science in ways that the *National Science Education Standards* (NRC, 1996) suggest.

At our first meeting, we discussed what our research questions would be. Formulating a research question was very difficult for me. What could I research as a first-year teacher that would be beneficial to anyone? I had no idea that many experienced teachers feel this way too (Hubbard & Power, 1993). Encouraged by my colleagues, I came up with an idea. My very first attempt was called "Teaching Other Content Areas Through a Science Perspective." Although I was unsure of what exactly I would be researching, I wrote up an abstract to send off

to an ethnography conference as a possible presentation of work in progress (Roberts, 1997). I have a strong belief that doing research should not be solely to improve teaching practice but also to share with other teachers who might be able to use what I have learned or experienced. The ultimate goal, of course, is to benefit students, particularly students like mine, many who come from low-income Central and South American immigrant families.

PARTICIPATING IN A RESEARCH FESTIVAL

Throughout my first semester of teaching, I had been making careful observations in the classroom. I tried to write my own reflections, as well as tape student discussions, make copies of student work I thought might shed light on this research, and from time to time, (when the school's video camera was available) videotape activities in the classroom. All of these are typical methods for teacher research that Hubbard and Power describe in their books (1993, 1999).

In December 1996, I participated in a Research Festival that Dr. van Zee (1998a,b) had organized to bring together students in her course on methods of teaching science and teacher researchers in the Science Inquiry Group. In preparing for this, I had been in a panic. There was no way I had anything that was defined enough to share with other teachers or methods students. I finally put something down on paper and shared it with some very eager, enthusiastic, and kind methods students, who appeared to be quite interested in what I had to say. All of the reviews of the Research Festival from the perspective of the methods students seemed to be favorable (surprise again!). One student wrote,

It was valuable because we got the chance to see and hear about teachers (real ones) helping students think and learn in a way that is compatible with what we have been learning in school. It has been very frustrating to hear what we learn does not fit in with the way the real world works, and these teachers have shown us that it can.

It was very motivating to me to be able to provide a firsthand view of what I was doing and to help create a vision for the methods students so that they could see that doing research is valuable, even for a beginning teacher.

RESHAPING MY RESEARCH QUESTION

My initial research question gradually was honed to "In what ways can I integrate science to motivate students to do expository reading and writing?" This happened

rather unintentionally. I had this great idea at the beginning of the school year to take my first graders on a nature walk. I wanted to find a way that I could integrate some expository reading, and felt that a nature walk might help provide motivation. As a result of the students' continual questions and observations about what was happening in the natural world outside of the building, we went on a walk to see what we could find that was nature. We had decided on a definition of what nature was after a lengthy class discussion, in which one student offered a fairly succinct definition—"Nature is anything that can't be made by people."

We each collected some nature items such as leaves, sticks, small rocks, acorns, wood chips, weeds, flowers, and moss. I had the children come back into the classroom, sit in a circle, and share what they had found. We then took turns gluing our own items to a piece of tag board. The children had generated many, many questions as a result of this activity. I made an experience chart by soliciting from each student one idea to share with the class.

Next, I modeled writing about what I had experienced on this walk. I asked the children to write about their experience, too. The children were eager to do just that. With a peer and then with me, they each shared what they had written. After some editing, and a little bit of research by one student about what kind of leaf he had found, each had one page to put into a book we made about nature walks.

I had not intended for this to be an ongoing activity. The students, however, began bringing things in from home and from recess. They were looking for books about trees and flowers, insects, squirrels, and seasons whenever they visited the school media center or browsed in our classroom library. They wrote in their daily journals about things they had observed on the nature walk, or their ideas on why things were the way they were. I was persuaded by the overwhelming demand of the students to keep up the nature walks on a monthly basis. They maintained their enthusiasm for reading and writing about nature. We ended up making five different class books.

After a few months of nature walks, a surprising thing happened. Because I was so focused (thanks to my research question) on this project, I started to notice that the children were no longer putting their collection items on the tag board randomly. They were beginning to become particular about where things went and what they were. Now I began paying attention to how they were putting their items on the tag board and why they put them where they did. I feel that their need to organize things sustained their motivation for expository reading because they wanted more information. Table 1 is a transcript of a conversation during the time we were putting nature items onto the tag board.

TABLE 1. CONVERSATION ABOUT THE NATURE COLLECTION

-
- 1 **Student 1:** Ms. Roberts, Ms. Roberts, Look what I got!
- 2 Ms. Roberts, what is it? Is it real nature?
- 3 **Student 2:** You got real nature, it looks like a bark to me.
- 4 **Teacher:** Let's sit down and make our nature collection.
- 5 **Student 3:** Where should we put the sticks?
- 6 **Student 1:** But what do I have? Is it a stick?
- 7 **Teacher:** Who has an idea about where things should go?
- 8 **Student 4:** Ms. Roberts, can we put the rocks at the top so they don't fall off and put the sticks at the bottom?
- 10 **Student 5:** I think we should do that, yeah, that's a good idea.
- 11 **Teacher:** Everyone OK with that?
- 12 **Student 6:** Who has brown leaves? I have brown leaves.
- 13 **Student 3:** I have sticks.
- 14 **Student 7:** Why are the leaves different colors? I have reddish brown ones.
- 15 **Student 8:** Because they are different trees.
- 16 **Student 9:** My mom said that they have different designs because they do.
- 17 **Student 10:** Can we get some more stuff? I didn't get any nuts.
- 18 **Teacher:** What nuts? Where do you see nuts?
- 19 **Student 10:** Like she has—those....
- 20 **Student 9:** These aren't nuts, these are acorns. Acorns with holes in 'em.
- 21 **Student 10:** Let me see the holes!
- Many students asking to see the holes.
- 22 **Teacher:** Let's pass that around so everyone can see.
- 23 **Student 10:** Why does it have holes? How did they get there? Can we crack it open?
- 24 **Student 9:** Don't crack mine!
- 25 **Teacher:** Maybe we can look for some others with holes.
- 26 Look on your way home from school today and see if you can find some with holes, and bring them tomorrow.

- 28 Let's start gluing things on the collection, ok?
 29 **Student 2:** Can I put mine on first?
 30 **Student 1:** Ms. Roberts, I don't know what I have. Do you know?
 31 **Students 8 and 2:** Let me see it.

Teacher holds up object and asks for input.

- 32 **Teacher:** Does anyone have any ideas about what this might be?
 33 **Student 2:** It looks like bark.
 34 **Student 7:** It looks like a moon thing because it has bumps on it.
 35 **Teacher:** What do you mean it has bumps on it?
 Why do bumps make it like the moon?
 36 **Student 7:** In my library book, there are pictures of the moon.
 37 and it has these. . . like bumps on it.
 38 But that thing is like a part of a tree,
 39 but it looks like the moon because it has bumps on it like the picture.

The students' enthusiasm for this activity was obviously high (lines 1-2, 17, 21, 23, 29). I was impressed that while we were making our collections, the students were answering one another's questions (lines 2-3, 8-10, 14-16) and not relying on me to be the central information source. They had also improved on the dynamics of conversation: they were able to take turns (lines 12-17), wait (at times) for one another to finish talking, and show they were listening by commenting on the responses they had been given (lines 21, 23, 24, 36).

Listening to the audiotapes of the children's conversations taught me many things. Often, I was able to hear conversations between two or three students who were talking at the same time the group was talking. Although they were not sharing with the class as a whole, they were obviously very much engaged in what was going on. I learned about myself, the ways I asked questions, the comments I attended to, and how many times I was talking when I should have been quiet.

PRESENTING AT NATIONAL CONFERENCES

In group sessions with my colleagues at two national conferences, I presented my findings as work in progress (Roberts, 1997; Roberts, van Zee, & Williams, 1997). In the evaluation of one of the sessions a participant wrote, "raised important issues about teaching, learning, and doing research. I was very impressed by

the depth of engagement with children—respect for a child’s thinking and work, their questions, and their multiple ways of documenting science learning, classroom as community, and teacher as inquirer.” These comments made me realize that even novice teacher researchers may have something to share that others may value and be able to use.

COLLABORATING WITH COLLEAGUES AT MY SCHOOL

My research journey does not end here, nor do the surprises and pitfalls. I am continuing to be a research practitioner in my classroom. A wonderful surprise came when I was able to persuade several other teachers in my school to try reflective research as well. We have our own branch of SING now at our site and presented as a group at the Ethnography in Education Research Forum this spring (Crutchfield, 1999; Harris, 1999; Kagey, 1999; Roberts & Bentz, 1999).

REFLECTING ON THE PROCESS OF BECOMING A TEACHER RESEARCHER

Another wonderful surprise came when I was able to bring my first-grade students back to the same physics lab I had been in as an undergraduate. We went to Dr. Layman’s class and the first graders had wonderful experiences using motion detectors. The prospective teachers were excited and pleased to have had the experience of interacting with “real live” students. I was able to share with them how I am using what I learned in this course, and how it has shaped my teaching. At the 1998 American Educational Research Association Annual Meeting in San Diego, California, I reflected upon what I learned from this experience by presenting “Physics and First Graders: What a Good Match!” The classroom that had laid the groundwork for me to become a teacher researcher had become a place of research!

After several cycles of presenting and writing, I had a paper published in a journal for teachers, *Science and Children*. This paper had its beginnings when my classmates and I had watched the moon in Dr. van Zee’s science teaching methods course in 1995. Then in 1997 I had collaborated with second- and third-grade teachers who were watching the moon with their students. We compared the questions our students asked and presented our findings in a paper together at an ethnography conference (Lay, Meyer, & Roberts, 1998). I had been surprised by the ways in which my students’ parents became involved in the moon watching during this project. The parents’ experiences became the focus of a

paper I presented at the International Conference on Teacher Research in San Diego later in 1998. Then I refined this and submitted it for publication early in 1999. Seeing my work in print in *Science and Children* was exhilarating!

Doing research has been a valuable experience for me. I have learned a lot about myself as a teacher, about students and the ways they think and learn, and about ways other people I have met at conferences also do teacher research. Even though first-year teachers have a sometimes overwhelming burden to bear, the time and effort put into teacher research was extremely beneficial to me. I have learned, through conversations with colleagues and others, that many teachers would rather hear or read about the research of a fellow teacher than read what they term “university research.” I would encourage all teachers, new and experienced, to take the opportunity to develop and pursue a research question that you have a burning desire to understand. It is more than worth the effort, although frustrating and nebulous at times.

Teachers who are considering doing teacher research might begin by attending conferences where teacher researchers are presenting. Encourage a colleague or two to try teacher research and support one another through the project. Read books written by teacher researchers, such as Karen Gallas’ *Talking Their Way Into Science*, (1995) and realize that she started in the same place we all start. I have heard her admit that research is at times a very frustrating journey, but a journey well worth taking. I wholeheartedly agree!

ENDNOTE

1. This study was supported in part by a grant from the Spencer Foundation Program for Practitioner Research: Mentoring and Communication to Dr. Emily van Zee, Science Teaching Center, University of Maryland. Opinions expressed are those of the author and do not necessarily represent those of the funding agency.

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Kids Questioning Kids: “Experts” Sharing^{1,2}

Marletta Iwasyk

As a kindergarten/first-grade teacher in an alternative school, I have much latitude in curriculum development and instructional methods. Questioning and dialog are an integral part of my teaching. The National Research Council states, “Inquiry into authentic questions generated from student experiences is the central strategy for teaching science” (1996, p. 31). I believe that children are capable of being teachers and while engaged in the teaching process, they reinforce and solidify their own learning.

To examine how this happens in my classroom, I conducted a case study to show children using questioning and communication skills during conversations about science (van Zee et al., 1997). The case study involved analysis of transcripts of students discussing the subject of shadows in which two students became the “teachers” or “leaders” and the rest asked questions for clarification or gave input of their own.

To document the discussions, I used a tape recorder with a microphone placed on a desk near the seated children. I also placed a video camera high in an unobtrusive corner. The camera was trained on the seats in the middle of the circle where I placed the “leaders” of the discussion. If other students had something to contribute, I asked them to step to the middle of the circle where I knew they would be visible to the camera. The object of the case study was to

record the children's talk while they discussed the subject of shadows to see if there was any carryover from the teacher-directed questioning/discussion activities. The focus of the study was not only the facts being presented, but also how the discussions took place.

EMPHASIS ON COMMUNICATION

From the first day of school, I model questioning and communication skills that I hope the children will emulate as the year progresses. Groups and pairs of children are allowed to converse a great deal during the day and so are comfortable speaking with one another.

The emphasis this year for the entire school is using kind and respectful words. I also stress the role of a respectful listener, which provides an environment in which children feel safe to risk speaking and sharing their ideas. As a class, we practice listening and speaking skills in many subject areas.

During "show and tell" time each week, the class president facilitates the sharing period, and the person called upon to share, in turn, asks for questions and comments from the rest of the class. As children respond to one another, I help them analyze and decide whether they are making a direct comment about what they heard. In the beginning, many children will add to the sharing rather than commenting on what was said (e.g., I have a dog too.). Also, their questions are usually too specific when asking for more information about what was shared (e.g., Is your dog's name Rover or Fido?). We talk about a better way to ask the question (e.g., What is your dog's name?).

Another opportunity for modeling questions comes when the class president is interviewed for stories that are written by each individual for the "president's book." Again, early in the school year, the questions tend to be very specific and limited (e.g., Do you like spaghetti? Do you like apples?). The children are encouraged to think in terms of general questions instead (e.g., What is your favorite food or fruit? What do you like to do on the weekends?). This clarification helps children to differentiate between types of responses and also determine appropriate times to make them. These skills carry over into other areas of study.

EMPHASIS ON SCIENCE

Science is wonder—that feeling of awe and excitement you have when you see a golden harvest moon, experience the power of the wind, see a rainbow, watch a salmon hatching, and experience the miracles of nature that take place around you. My school, which has an environmental and art focus, greatly values this view of science and nurtures it in every child's heart and mind. It is then a natural step to go from this “wonderland” of experience and appreciation of nature to the world of discovery and the desire to find out the “why and how.”

And so, science is wondering, wondering about our physical and biological world—and young children wonder most of all! They have a natural, eager intellectual curiosity about the world around them and want to find out all they can, as evidenced by the many questions they ask. The dilemma for a teacher of young children is how to keep this natural curiosity alive within the confines of the classroom. Time, lack of materials or space, or other obstacles—such as a feeling of inadequacy in science knowledge—may limit the amount of experience the teacher provides in the area of science.

One successful activity that I have used to keep this connection to the world outside the classroom is the study of light and shadows, using, of course, the most visible object in the children's sphere of reference—the sun. Learning about objects in the sky, including observing the sun and its movement, is one of the science benchmarks for kindergarten through grade two (American Association for the Advancement of Science, 1993). Much of my knowledge about the sun was gained in a physics program for teachers at the University of Washington (McDermott, 1996).

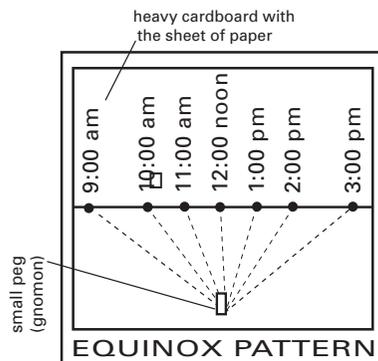
SHADOW DISCOVERY

On the very first sunny day of school in the fall, we begin our study of shadows. This is a natural and easy way not only to nurture curiosity and wondering, but also to help the children develop the skills and attitudes that will make them successful lifelong scientists whether or not they go on to choose a career in a scientific field.

Figure 1 lists some suggestions for various shadow activities. During these shadow activities, many observations and recordings are made and compared throughout the year. Many questions arise, such as, “Why does my shadow change shape, length, and direction?”

**FIGURE 1. ACTIVITY SUGGESTIONS FOR SUN PLOTS AND SHADOWS:
OBSERVING SHADOWS, RECORDING DATA, AND COMPARING**

- ▶ Take a walk on the playground and observe shadows of poles, trees, and walls.
- ▶ Take a walk with your shadow and observe how it follows wherever you go and does whatever you do.
- ▶ Have your class stand in a circle and discuss shadows they see—some are in front, some are behind. Discuss orientation if children want to make a claim about the shadow position. (If students say, “The shadows are in front of us,” ask, “Are all the shadows in front?” If the children say no, then ask, “How can we make that happen?”) Ask questions that help children see that everyone needs to be facing the same direction to see their shadow in front, behind, and so on. This can be facilitated by the use of a “shadow line” (discussed below) that is close to where your class lines up everyday. I have my class line up on the “shadow line” after every recess whether it is sunny or not. If it is sunny, then we can quickly make some observations, think about some questions, and have a short discussion before coming in—very efficient and easy to do. (At this time, I do not say whether a conclusion is right or wrong; I ask them to think about it.)
- ▶ Line up on a North-South line (if possible) on the playground. This orientation helps children see the shortest shadow pointing North at local noon. Give directions to your class, such as the following: Stand so that your shadow is in front of you (or behind, beside on the left, right). Which way is your shadow pointing? Toward the building or away from it? Is it long or short? Longer or shorter than this morning? Last week? There are many questions you can ask to promote thinking and stimulate observations.



- ▶ Make a sunplot/shadow board (see above) for children to study shadows independently at home. To make the sunplot/shadow board, use heavy cardboard and stick a small nail (or other similar object) into the center. A sunplot/shadow board is placed in the same spot throughout the day. Children mark the end of the shadow (noting the time and date) using a piece of heavy cardboard with a sheet of white paper. Students can then observe the pattern the dots make, if connected.
 - ▶ Train two children to use a sunplot/shadow board. Discuss the use of a gnomon, which is a straight object (peg, stick, rod) used to cast a shadow, and how to record data (length, time of day). Take as many readings as possible each day. The first team then trains the next team (a classroom job). If inside, shine a flashlight or bulb into the sunplot board to make “artificial” shadows (peg boards work well). This is a good exploration activity.
 - ▶ On equinoxes and solstices, record the end of the shadow throughout the day on the playground with chalk and then use paint to make it permanent for future reference. A tall pole on a sturdy base works well as the gnomon for this (mark where the base goes).
 - ▶ Transfer information from daily records to overlays for use on an overhead to compare fall, winter, and spring shadows (length, shape of line connecting dots, sun’s position). Overlays are good for end-of-year discussions.
 - ▶ Enrich the activity with shadow puppets, poems, journal writing, and literature.
-

In the beginning, I do not answer any of the questions; instead, I ask the children to think about the questions and discover how they can find the answers for themselves. If they make early conclusions about what they observe, I do not acknowledge any answer as right or wrong. It isn’t until after the winter solstice, when the shadows are becoming short again, that we have an in-depth discussion of what we have learned about the sun and shadows, with the children facilitating as much as possible. To make this happen, much groundwork has been laid during the year to this point.

DISCUSSION OF SHADOWS

Teaching Standard B in the *National Science Education Standards* (National Research Council, 1996) states, “Teachers of science guide and facilitate learning. In doing this, teachers orchestrate discourse among students about scientific ideas” (p. 32). See Table 1 for an example of dialog that took place during a discussion of shadows, which typically lasts anywhere from 15 to 30 minutes, depending on interest and focus.

**TABLE 1: STUDENT CONVERSATIONS ABOUT SHADOWS
ON FEBRUARY 4, 1997**

(Responses are noted by initials: T = teacher, * = male student, and ** = female student.)

L*: I think I know how they are made.

T: The shadows?

L*: Uh-huh.

T: Would you like to come on up here and be our second “scientist” then?

L*: (After positioning himself in the middle of the circle.) If there was a bright, bright light up here, and it goes like you were talking about (responding to the information C*, the other facilitator, had previously shared), and then you could be right here and you’re covering part of the ground and you could be however you want.

C*: I know. That’s what I said.

L*: Like if we were outside you can almost always see it on grass.

T: OK. Have a seat there and you can answer any questions these people have.

C*: (Calls on R*)

R*: How, I mean like.... Why does(n’t) it have the color that you have on?

C*: It doesn’t.

R*: But why doesn’t it?

T: (Clarifying question) Oh, so, why doesn’t it have the color that you have on?

C*: It’s not really you, its just....

R*: A part of you.

C*: Yeah, it’s just a reflection of you.

R*: Oh, okay.

C*: Black on the ground.

L*: Like the sun, like you're, you're, like you're a dark black cloud.

T: Ooo, we'll have to write a poem about that!

M***: I see a shadow in the room.

T: Oh, you're looking at your shadows in the room?

Everyone sees shadows on the shades with sun shining through the windows. There is great excitement and everyone is talking at once.

At the beginning of our discussion, the children posed questions they had thought about in connection with shadows, and these were listed on a KWHL chart as shown in Table 2 (e.g., Where do shadows come from? Can they see?). In the course of the discussion, two male students who had a lot to share became the facilitators for the discussions, calling on others for questions or comments. In doing this, I turned a possible negative (two male students dominating the conversation) into a positive by asking the two "leaders" to explain some of their statements. The two student leaders became quite humble at some points saying "I don't know" when asked a question.

TABLE 2. A KWHL CHART.

K	W	H	L
What do I Know about _____?	What do I Want to know about _____?	How can I find out about _____?	What did I Learn about _____?
(Prior knowledge or preconceptions. All ideas are listed.)	(Questions that students have.)	(Books, Internet, asking others.)	(Facts learned may be different from those listed under K.)

At first, the student leaders called on their friends (also male). The naturally quiet students were not as involved at the beginning, but as time went on, they joined in when called on or when they just wanted to speak. Soon, everyone was participating, both males and females. For the final discussion, when I facilitated, all but one female shared.

One of the questions asked and discussed was “Why doesn’t it (the shadow) have the color you have on? This student wondered why the shadow wasn’t the same color as skin. Throughout the discussions, many moments of spontaneous dialog occurred among the children. They were all respectful and involved listeners. Because of the accepting attitude of the group, no laughing or put-downs occurred, even if an idea seemed far-fetched. Some disagreed with statements but were willing to suspend judgment and try to find out for themselves. Also, spontaneous moments might be seen by some to be negative, but these were some of the more positive moments in my view. They showed that the students were really involved. It was enjoyable to just sit and listen to them as the children tried to explain their thoughts and communicate their ideas to the group, asking questions of each other for clarification. I plan on having more discussions during the rest of the year, with other students being the leaders.

LEARNING FOR ALL

Questioning techniques can be used by students to learn how to ask questions of themselves or of others to investigate or explore a topic of interest. Questions allow a child to become the leader or teacher as he or she enlarges or guides the discussion in a specific area, whether they are the ones asking or being asked. I firmly believe that as one teaches, one also learns; thus, children grow in their own skills as they teach others.

Just as questions can help children clarify their own thinking, the teacher can learn much about the students by listening to their discussions. It was very enlightening for me to observe thinking processes as the children gave explanations. I also gained insight into class dynamics. During the shadow discussion, the original leaders were male, but in many subsequent discussions, the females took the lead. I will continue to heighten my awareness of participants in discussions, making a special effort to draw in the quiet ones and encourage student leaders to do the same. My goal is to empower the students to have a role in their own education!

ENDNOTES

1. This article is reprinted with permission from NSTA Publications, copyright 1997 from *Science and Children*, National Science Teachers Association, 1840 Wilson Blvd., Arlington, VA 22201-3000.
2. Development of this case study was partially supported by a grant from the National Science Foundation (MDR-9155726) to Dr. Emily H. van Zee. Opinions expressed are those of the author and do not necessarily represent those of the funding agency.

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Eyes on Science: Asking Questions About the Moon on the Playground, in Class, and at Home^{1,2}

Akiko Kurose

I stop, it stops too. It goes when I do. Over my shoulder I can see. The moon is taking a walk with me. (L. Moore, 1974)

Observing the moon gives children experience in making discoveries in a cooperative way that allows them to discover that everybody on planet earth is sharing the same phenomena. While you can't grab the moon, push it around, or change its position, you can see it, draw pictures of it, and talk about it. Table 1 shows some questions I ask my students throughout the school year. Since I learned about the moon in a special physics program for teachers at the University of Washington (McDermott, 1996), noticing the sky has been a favorite activity with my students.

TABLE 1. QUESTIONS THAT ARE THE BASIS FOR CONVERSATIONS ABOUT THE MOON

INITIAL QUESTIONS:

- ▶ What can you tell me about the moon?
- ▶ Please draw a picture of the moon.

- ▶ Where can you see the moon?
 - ▶ When can you see the moon?
-

ONGOING QUESTIONS:

- ▶ Where did you see the moon?
 - ▶ How high in the sky was it?
 - ▶ When did you see it?
 - ▶ What kind of moon did you see?
 - ▶ Please draw what you saw.
 - ▶ Are all the drawings the same?
 - ▶ Why do you think some are different?
-

OBSERVING THE MOON

The *National Science Education Standards* (National Research Council, 1996) suggest that children from kindergarten through second grade should learn about objects in the sky by observation. My first graders and I frequently go out and look at the moon at different times of the day so the children can view the moon in a variety of phases. In the afternoon, the southern sky sometimes gives students an opportunity to see the waxing crescent moon. In the morning's western sky, we sometimes observe the waning gibbous moon. During our viewings, neither the students nor I use many words to explain what we see; we simply observe. So that they become aware of the position of the moon, I have them draw the moon in relationship to the horizon. (See Figure 1.) As the children gain experience they draw the sun on the same side as the lit part of the moon.

Engaging in this type of observation enables students to illustrate the different phases of the moon, keeping in mind its relationship to objects on the horizon. I encourage them to make predictions as to when and what the next phases will be. I also invite them to reflect on the phases of the moon previous to the moon they have illustrated. Eventually, students are able to seriate the different phases of the moon as well as identify which ones will set in the evening and which in the morning. (See Figure 2.)

FIGURE 1. STUDENT'S DRAWING OF THE MOON DURING RECESS EARLY IN THE SCHOOL YEAR

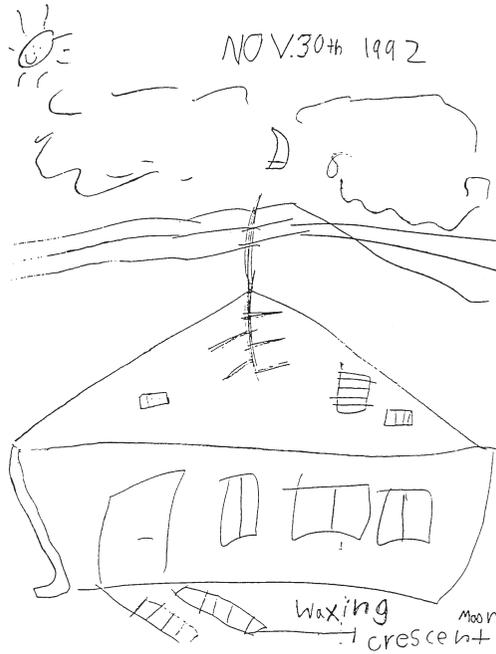


FIGURE 2. EXAMPLE OF STUDENT'S SERIATION OF THE MOON EARLY AND LATE IN THE SCHOOL YEAR



Students then express themselves creatively, demonstrating their knowledge as well as their appreciation of the moon by writing prose and poetry relating to its phases. (See Figure 3.) I also read stories about the moon and sun from other cultures such as *The Truth About the Moon* by Clayton Bess (1983).

FIGURE 3. STUDENT'S POEM AND DRAWING OF THE MOON



Watching the moon can easily be transferred into the child's home. Initially, parents say, "We don't let our kids stay up that late. And what is this, telling them to observe the moon at night?" But parents delight in learning from their young. Time and time again excited parents come to school, using the terminology their own children have taught them: "waxing, waning, and gibbous" and admitting that they "didn't know what those things were." As their children point out to them the waxing moon setting, the parents recognize that the moon is visible during suppertime, at sunset, and also when the children go home from school.

Similarly, they discover that the waning gibbous moon is observable in the mornings and into the class time. Parents have reported that when their children get up in the morning, they are so excited when they see the moon. Students are also able to observe the waning moon, which they illustrate during morning class time.

STUDENT'S QUESTIONS ABOUT THE MOON

Some colleagues and I have been developing case studies of questioning during conversations about science. Below are examples of questioning by my students.

When Stella went on a month's visit to Australia with her family, her assignment had been to keep a record of the phases of the moon while she was there, using the same format as her classmates in Seattle. When she returned, we made a comparison of her recordings in Australia with those of her classmates. Figure 4a shows her observations in that country, where the waxing crescent moon appeared to be lit on the left. Figure 4b shows her classmates' observations in Seattle, where the waxing crescent moon appeared to be lit on the right. The children and I asked her to share her observations as well as explain why this phenomenon occurred. For discussion, we used a globe and a map on the floor. Australia is in the southern and Seattle in the northern hemisphere. Some of the children lay on the floor and realized that if they are upside down something lit on the right looks as if it is lit on the left. One child asked what it would look like on the equator. See a transcript of a conversation about the observations of the waxing crescent moon in Australia and Seattle in Table 2 .

At other times, I ask the children to write down their own questions to share and compare with one another and try to come up with some answers. "What would the moon look like on the sun?" and "Why is there a moon?" are examples. During circle time, I ask students for more questions about the moon and tell them to think about the whole planet earth and not just Seattle. These are some of the questions that they develop: "How did the moon turn into different phases?" "This morning I saw a very thin moon. What kind of crescent moon is that?" "How can the moon be rising in the morning?" "Why does the moon follow me?" "Why does the moon look different in Hawaii?" "Does the moon look different in Africa?" "What does earth look like from the moon?" "Do they see different phases or do they see the whole earth?" "Why does the moon look the opposite in the mirror?" "What does the moon look like on the equator?" I also ask the students how they would get information about the moon and they suggest the dictionary, encyclopedia, a trip to the library, and looking at the moon.

FIGURE 4A. STUDENT'S OBSERVATIONS OF THE WAXING CRESCENT MOON WHILE VISITING IN AUSTRALIA

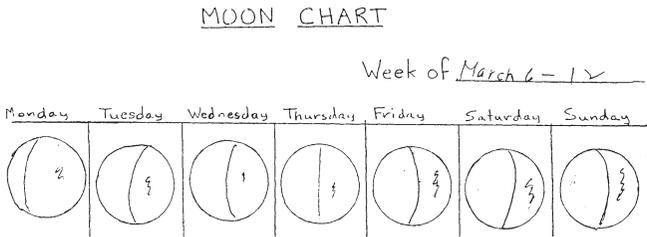
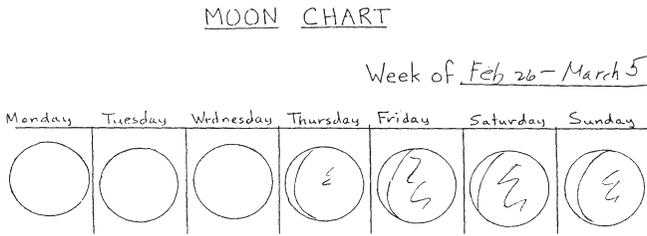


FIGURE 4B. STUDENT'S OBSERVATIONS OF THE WAXING CRESCENT MOON IN SEATTLE

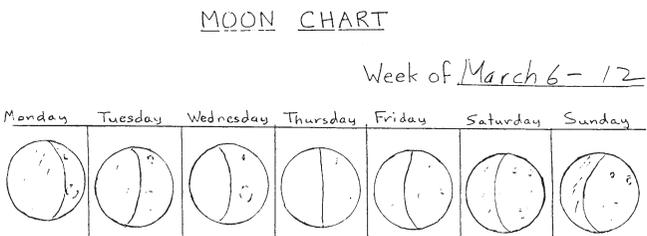
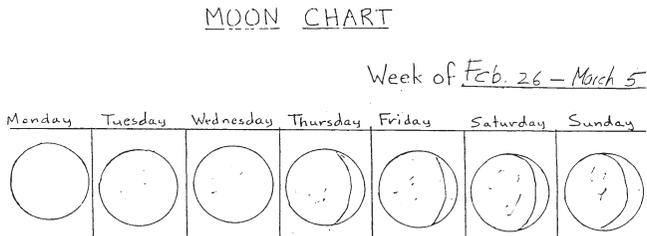


TABLE 2. TRANSCRIPT OF CONVERSATION ABOUT THE OBSERVATIONS OF THE WAXING CRESCENT MOON IN AUSTRALIA AND SEATTLE

We compared the observations of the moon in Australia by a student, Stella, with her classmates' observations of the moon in Seattle.

Teacher: Stella, do you want to tell us about your observations in Australia?

Stella: The waxing crescent moon was facing the other way.

Teacher: The waxing crescent moon was facing the other way? Why do you think it was facing the other way?

Stella: It was on the other side of the world.

The children and I found Australia and Seattle on a globe. Then Stella drew her observation on the board, a crescent moon curved on the left.

Student: It's like the waning crescent.

Student: I thought it was like this! (The child turned upside down.)

Teacher: That's right. When he lies down on the ground he sees it the opposite way.

Then we discussed how the waxing crescent moon would look in Canada.

Student: Right side up.

Teacher: What do you mean right side up?

Student: The way we see it.

Teacher: Do you mean the way we see it in Seattle?

Student: Uh, huh.

Teacher: In Australia, do you think they would think they're upside down?

Student: No. Maybe. Stella thought so.

Teacher: For them, they would think that they're right side up, wouldn't they? It's just that they see it from a different perspective.

We also discussed how the moon would look in Florida and other places.

Student: My dad's been to Brazil.

Teacher: How do you think you would see the moon there? Remember where the equator is. Make a hypothesis.

Student: The way Stella saw it in Australia.

Teacher: The way that Stella saw it in Australia.... So it depends upon where you are on earth.

Student: How does it look if you're on the equator?

INTERPRETING FIRST-GRADERS' QUESTIONS ABOUT THE MOON

Studying the phases of the moon at a first-grade level is appropriate and challenging to students. Not only do they become enthusiastic about the learning process, their feelings are sustained.

My students look forward to the observations because they empower them to know what's going on in the sky. When students reach the point at which they are able to comprehend what they are seeing, they celebrate their discoveries and take ownership of them. The process of observing the moon becomes part of their daily experience and becomes cooperative in nature as they are able to share with their families and fellow students what they have learned and observed.

The children's experiences in our daily moon gazings over a period of several months also nurture their abstract thinking and questioning skills. In one conversation about observations, a child casually inquired, "how does the moon look if you're on the equator?" This question was neither prompted nor expected. I do not make it a practice to feed questions. Because of the manner in which we study the phenomena of the moon, children's queries are real. And because their curiosity is piqued, the answers have meaning. As a child at that age, I never entertained such questions because I had not been given the opportunity to study the moon in an organized way through observations, and it would not have occurred to me to think about what the phases of the moon would be like from any part of the world, including my own home. In discussing their observations, the children sometimes relate a shared experience—the feeling that the moon is following them. This experienced relationship with the moon leads naturally to inquiry. Other children have become interested in learning about the way the moon looks from different places on the earth and away from the earth such as on the sun. Several children were also curious about how the earth appears from the moon. These experiences engender thoughts about the moon from different places, granting the students the gift of a global perspective. Engagement in this type of abstract thinking and questioning has become part of our class culture, in which virtually all of the children participate.

Teaching about the moon is accessible to all teachers. It is truly an "eyes-on," "minds-on" curriculum. This kind of study is spontaneous and exciting for students, parents, and teachers alike. The students experience physical as well as mental freedom as they observe, cooperatively discuss their questions, and work with one another. Questioning strategies are important in encouraging and inspiring students to pursue their interests and engagement in dialogue about

their experiences and realities. This curriculum integrates all the disciplines in a natural setting: science, mathematics, multicultural studies, reading, writing, language arts, music, and art all fit into the theme.

ENDNOTES

1. Development of this case study was partially funded by a grant from the National Science Foundation (MDR-9155726) to Dr. Emily H. van Zee. Opinions expressed are those of the author and do not necessarily represent those of the funding agency.
2. This paper was presented at a workshop, "Teachers as Researchers: Studies of Student and Teacher Questions During Inquiry-Based Science Instructions," at the 1997 annual meeting of the American Association for the Advancement of Science in Seattle.

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Tapping Into Children's Curiosity¹

Rebecca Kwan

Curiosity drives the quest for knowledge. Curiosity brings wonders and questions. It then generates actions to answer questions. Curiosity is the basic spirit of science learning. A child's curiosity can be ignored because of the teacher's agenda.

In this case study, I followed up on a question one of my first-grade students had asked in social studies: "How come rain won't go through the roof?" His question arose while I was reading to the class from a page on thatched houses in Japan in *Houses and Homes Around the World* (Karavasil, 1986). I decided to develop a lesson on constructions based on this child's question and my county's science curriculum (Westley, 1988).

As a way of learning science integrated with the county curriculum for social studies, I had my students start to figure out "How can I make the roof with straw so that it won't leak?" I thought trying to figure out this question was a wonderful spin-off topic for my students while I was teaching topics such as building materials, shapes, and the motion of shapes. This lesson would also be a way to assess students, which would fit nicely with the requirements in the Maryland School Performance Assessment Program. Students were to determine ways to make a roof with straw so that it wouldn't leak. The lessons took two sessions for exploration and testing.

We started the exploration session by brainstorming various possibilities for making a waterproof roof. The students came up with four different ideas: to braid the straw tightly, to tape the straw on, to glue it on, and to weave it on. I provided students with these materials to explore: backyard grass for straw, green plastic strawberry baskets from the grocery store for a triangular roof frame, a science research work sheet to record their findings, and glue, tape, and scissors. From the beginning of this exploration session, the students were excited and highly stimulated.

The students investigated the several ways that had been suggested of handling the straw and basket. Some of them tried to braid the straw but the grass was too dry and broke as soon as they tried to twist it. They tried hard to have the glue stay on the plastic lines of the baskets. At first most of the glue dripped down between the plastic lines and the students did not know they needed to wait for the glue to dry before the straw would stick there. They struggled to weave the dry grass in and out of the narrow openings and their fine motor skills weren't sufficient. For some, it was the first time ever to attempt to bend tape around to form a loop in order to stick one side on the plastic and grass on the other side. There were a couple of students who had the small motor skills to weave away merrily. I was in awe with how the students' assimilated these skills. Some of the frustrated students turned their energy to imitating the ones who had succeeded in weaving and did a great job of it. By the time the second session started, most of my first graders were happily doing their weaving, gluing, and taping.

The second session ended with the testing. By this time, some of the roofs were quite appealing yet not finished. I took a gallon bucket full of water and a paper cup to test our theories. I poured water down the roofs and asked the students to observe. The students were fascinated by the water movement and excited to see water not passing through the part with more grass while passing through only the part with a couple of strands of grass. Some of the students took their roofs to test under the faucet in the sink. I handed out papers for them to record the results and asked them what they had learned. The conclusion was unanimous that they need to fill in the holes with more grass on the roof.

Teaching according to the students' curiosity requires a radical change in perspective from that which comes most easily to instructors. The waterproof thatch roof lesson was a modification of a lesson from the previous year, which had emphasized the effect of the direction of thatch on the water run-off. Since leaking was not the issue, I had used cardboard paper as the roof frame. But, when my student asked the question, "How come the roof doesn't leak?" I needed to come up with an activity to fulfill that curiosity. Modification of materials and

method was needed. This is an example of teaching for understanding so that, as the standards proposed in 1996 by the National Research Council suggest, "activities and strategies are continuously adapted and refined to address topics arising from student inquiries and experiences"(p. 30). I was glad the students were enjoying their lessons and I took pleasure in watching them learn through their own discovery and gain physical skills along the way.

ENDNOTE

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Giving Children a Chance to Investigate According to Their Own Interests¹

Constance Nissley

As a science teacher in an independent school, I work with children from kindergarten through fourth grade. I have found that children enjoy having a chance to explore with materials in an unstructured time that allows them to shape their own investigations. In addition to class time under my direction, we schedule from twenty to thirty minutes each week for every class to have what we call Choice Time. During this time, students choose their activities, get out the materials, investigate, and then clean up.

Many of the activities are described in Table 1. The materials are on open shelves so that they are easily available to the students. Students may also request materials for additional activities they would like to explore. Sometimes these are extensions of other class activities, such as the electric circuits. At other times students have been continuing observations after a demonstration by a student or me: for example, working with siphons, putting on goggles and testing the popping power of ingredients that form carbon dioxide in vials with lids, or investigating electroplating.

TABLE 1. MATERIALS AND ACTIVITIES AVAILABLE FOR CHOICE TIME

Visiting and observing live animals. We have guinea pigs, hamsters, a rabbit, finches, quails, a frog, a turtle, a lizard, fish and snails in fresh water, and crabs and snails in salt water. The mammals can be held or placed in mazes made on the floor using blocks. All the animals can be fed and their behavior observed. Occasionally one of the animals has had babies, so that we have had opportunities to observe life cycles and development.

Mixing simple chemistry. Dropper bottle of diluted vinegar, baking soda solution, bromthymol blue solution and red salt water can be mixed in trays with small wells or in vials. Medicine droppers can be used to transfer mixtures. This selection of solutions works well because they form bubbles, the acid/base indicator changes from blue to green to yellow, and colored layers can form if added carefully. When mixing is done thoughtfully, children can make a variety of colors. At times cabbage juice can be added for additional colors.

Simple electric circuits. Circuits can be created by use of batteries with holders, wires with alligator clips, bulbs in holders, buzzers, and switches. The battery holders lend themselves to connections for both parallel and series circuits.

Magnets. Magnets of various strengths, sizes, and shapes can be manipulated with various materials—metals and non-metals—for testing interactions.

Computer. The favorite activity is the coral reef ecosystem game, *Odell Down Under*. The challenge is for various fish to keep alive by finding their food and avoiding predators.

Capsela. This motorized set can be constructed to have its motor simply make a fan propeller go or to make it a more complex wheeled vehicle that can go forward or backward with a switch.

Light and color. A box from the *Elementary Science Study* curriculum unit, “Optics,” with a two-hundred watt light bulb shining through openings, is used with such supplies as colored filters, mirrors, prisms, and diffraction grating glasses.

Examining and comparing rocks, fossils, bone or shell samples.

Observing frog development. In the spring, we observe development of wood frog eggs to tadpoles and then frogs. These eggs are collected from our pond and returned as they mature into tiny frogs.

Certain activities like the following may be assigned during part of Choice Time to give each child a responsibility for a task or project shared by the class:

Animal care. Checking and filling water bottles and food dishes for the animals is an activity that I assign to students in rotation, unless children choose the activity. Some students like to change the chips in the cages, but it is not required.

Temperature graph. When a class is studying weather or a country in social studies, we may keep a record of daily temperatures. Placing a strip of masking tape along a marked line of a laminated sheet, the student colors in a bar of an appropriate length for the temperature observed on an outdoor thermometer. This strip is taped in place on the ongoing graph being created each day that the class is in the science room. When we are studying a country, we create a parallel graph. Each day we obtain from the Internet the temperature in the country's capital.

In this case study, I am interested in what amount and quality of journal writing is appropriate in this context. I have been investigating how to encourage the students to communicate their observations and understanding of their investigations. By their own choice, the students sometimes repeat activities in many variations. They find this more interesting and easier, however, than explaining what they have done and observed.

The usual format has been for students to record comments in their Science Log booklets. Originally I had asked them to write about what they had learned from their investigations or something new that they had observed. For the first time in our science classes, they were asked to write about self-chosen and self-directed activities. So the comments also had to be independently created. Although they have had experiences of journal writing in Language Arts and have recorded observations in science investigations directed by a teacher, many students wrote very little. In addition to being very brief, what they wrote was vague, such as "Chemistry is fun" or "I like Pumpkin" (the hamster). I have tried several ways of encouraging more extensive descriptions or more analytical comments. For example, I have asked students questions such as "What about chemistry is fun?" and then "What did you need to mix to get the bubbles?" and "What other powder or liquid might you add to get bubbles?"

Among group experiences that have helped students have an idea of how to write about their own investigations has been to start the class with a demonstration, such as placing a small bottle of blue hot water in a larger container of cold water, and asking students to write a description of the observations and an explanation. This has given us a chance to discuss observations made by individuals and what makes a good record of these.

Another approach is to follow a demonstration with a class discussion that gives students a chance as a group to share observations and build an explanation for their observations. For example, I did this after folding three pieces of paper into a cylindrical shape, a triangular column, and a rectangular column and testing which would best support a book. This produced a lively discussion among the students of why the cylindrical shape was the best support, getting to the idea in their own words that the circular top more evenly distributed the weight. One difficulty in the discussion, of course, was that a few students were most anxious to talk about their ideas and others didn't like to share in this setting. The students also needed reassurance that their ideas were valid and didn't need to be referred to the teacher's authority all the time. The discussion provided a way that was not very threatening for a student to question another's idea that differences in amounts of scotch tape were the reason for differences among their observations. They could make further observations and interpret them.

Another way to encourage both careful manipulation of materials and clear explanations of what happened is to ask each student to prepare a demonstration to present to the class. The presentation includes leading a discussion of the outcome and possible explanations.

We feel that all of these experiences have allowed students to follow their own interests more than would be provided otherwise in the curriculum. Also they focus individually on some analysis of their investigations.

Table 2 shows examples of the development of log writing for three third graders over a semester. These logs show increases not only in the detail of observations but in evidence of the thinking that was involved in their investigations. The last entry for each student includes brief statements of interpretations of these observations.

TABLE 2. EXAMPLES OF THE DEVELOPMENT OF SCIENCE LOG ENTRIES BY THIRD GRADERS DURING A SEMESTER

D.H.

9/16: I did siphons. I made different colors.

10/7: We cleaned lots of cages. They smelled really bad.

10/28: I was at electricity. Me and C. made bulbs light up. We made the buzzer sound.

1/20: Today M. and I did chemistry. We made explosions out of soda and vinegar. Some of them were big and some were small. The big ones we had to do outside. We used little tubes to put the soda and vinegar in. It was fun.

J.F.

9/16: I did Capsela.

10/7: We cleaned the animal cages. It was a lot of fun. The cages stink!

10/28: I did chemistry. I made a secret ??

1/20: In electricity, I made a huge circuit. I made a switch out of a light bulb. (Oral explanation later: The buzzer went on when the bulb was screwed in but the bulb didn't light.) The circuits were very interesting. We made the buzzer very loud.

L.Y.

9/16: I did siphons.

10/7: You have to shake the bubble out of the tube in siphons.

10/28: I did animal care. It was smelly because of all the pee.

1/20: I did mammals with L., and we played with Kuby and fed him carrots and celery. He preferred celery. I also did the computer for the ice cube experiment. I found out that mine was alive for 7½ hours.

The planning of this program relates to the teaching standards specified in the *National Science Education Standards* (National Research Council, 1996). This is an example of planning and development of a science program to guide and facilitate inquiry in an environment that provides students with time, space, and resources needed for learning. Choice Time and many of our other activities relate to Content Standard A in the *Standards*: All students should develop the

abilities to do scientific inquiry and understand it (p. 121). The activities are related to Content Standards C, D, E, and F: physical science, life science, earth and space science, and science and technology.

ENDNOTE

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How Does a Teacher Facilitate Conceptual Development in the Intermediate Classroom?^{1,2}

Judy Wild

As children investigate and explore the world around them in their preschool and primary years, the curiosity and creativity of a scientist seem natural to them. Continuing to nurture that enthusiasm within a structured science curriculum that enables students to develop scientific concepts is an awesome task for teachers. Studies in recent years report that students, especially at high school and college levels, hold misconceptions or preconceptions about natural phenomena (Driver, 1985; McDermott, 1990). How can teachers, especially in elementary science classes, facilitate conceptual development so that the knowledge the students construct is aligned with that of the scientific community?

Conceptual understanding is developmental; students must therefore be engaged in activities that are of interest to them and at the appropriate stage of their growth. Concrete activities, such as interacting directly with materials, help students to have a basis for shaping concepts and abstract reasoning. Adequate time is critical so that students may begin developing ideas and refining them.

An inquiry-oriented approach to science has been advocated by science educators for many years and is a major goal in both the *Benchmarks for Science Literacy* published by the American Association for the Advancement of Science in 1993 and the *National Science Education Standards*, which the

National Research Council issued in 1996. As students learn to question what they observe and search for answers, schools can provide a framework for their curiosity. Inquiry as a way of thinking and learning can enable students to develop knowledge and skills, to identify and solve problems, and to make informed decisions. Such a framework can extend learning beyond the science curriculum and beyond the confines of the classroom.

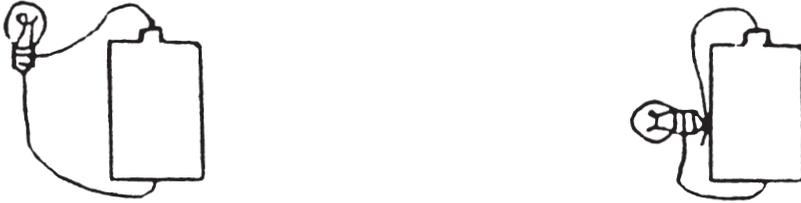
In inquiry applied to the study of electrical energy at the intermediate level (Educational Development Center, 1966; Lawrence Hall of Science, 1993; McDermott, 1996), students cultivate an understanding of ideas such as simple circuits, conductors, non-conductors, short circuits, series circuits, and parallel circuits. How can teachers assess their conceptual development and assess how the understanding that the students are arriving at compares with that of the scientific community?

Students need opportunities to communicate their ideas as they develop concepts. Discussing these with a partner, a small group, or the entire class, as well as writing about their learning, helps them to formulate and refine their understanding and makes their thinking known to others. Asking students “why” is important in assessing their understanding. Questions such as these are helpful: What do you observe? What do you infer? Why do you believe...? What is the evidence for...? How would you operationally define...?

In asking fourth-grade students to explain the reasoning for their observations and beliefs during lessons on batteries and bulbs, I discovered that at times it was difficult for some students to expand or apply their understanding of electrical circuits. Revising lesson plans to provide additional activities was necessary in these instances to help the students with conceptual development. Here are some examples of lessons in which students needed additional experience to help expand or apply their understanding of electrical circuits.

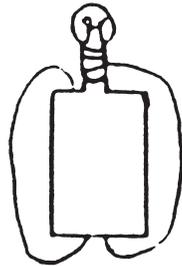
After one or two lessons, most students were able to identify correctly the two ends of the wire, the two ends of the battery, and the two ends of the bulb and to state that these ends needed to be included to make a circuit. But some students could not apply this generalization when predicting whether new configurations would light. (See Figure 1.) Whether the bulb was touching the battery directly was a factor in their predictions. Students needed to experience this idea in a variety of ways. Four or five lessons were necessary for some students to predict correctly circuits that would light in all or most of the configurations they drew or were given.

FIGURE 1. EXAMPLES OF CONFIGURATIONS WHERE THE BULB WAS NOT TOUCHING THE BATTERY DIRECTLY AND STUDENTS RESPONDED INCORRECTLY THAT THE BULB WOULD NOT LIGHT



Students had difficulty recognizing that connecting a wire to a battery that was already part of a completed circuit with a wire and a bulb resulted in a short circuit. Setting up a short circuit and connecting and disconnecting the wire without the bulb while observing the light going off and on helped students to identify a short circuit correctly on later evaluations. (See Figure 2.)

FIGURE 2. EXAMPLE OF SHORT CIRCUIT



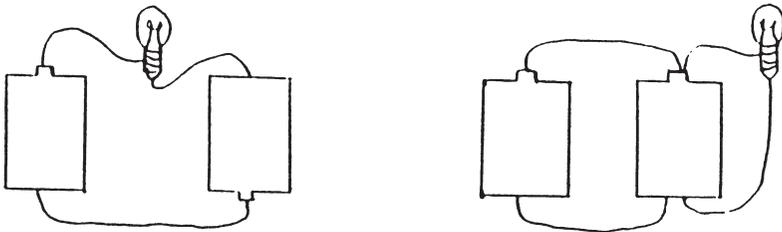
Some students who could identify short circuits correctly when given drawings of batteries and bulbs with wires were unable to add wires to drawings of batteries and bulbs only so that the bulbs would light. They drew additional wires that resulted in short circuits. (See Figure 3.) Setting up the circuits with batteries, bulbs, and wires as they had drawn them helped students to identify which circuits were short circuits and on later evaluations these students could add wires to drawings of batteries and bulbs that did not cause short circuits.

FIGURE 3. EXAMPLES OF DRAWINGS BY STUDENTS THAT RESULTED IN SHORT CIRCUITS



Some students were able to identify series and parallel circuits when two batteries were touching each other but not when the batteries were connected by wires. Additional activities setting up circuits with batteries, bulbs, and wires, making and checking predictions, and recording and discussing results helped students on later evaluations to identify series and parallel circuits when the batteries were not directly touching. (See Figure 4.)

FIGURE 4. EXAMPLES OF CONFIGURATIONS WHERE BATTERIES ARE CONNECTED BY WIRES AND STUDENTS RESPONDED INCORRECTLY THAT THE BULB WOULD NOT LIGHT



As lessons progressed, students could develop ideas about the flow of electrical current by using the brightness of the bulbs as an indicator of the amount of current flowing. Questions such as these were to elicit thinking while the students developed an electrical current model: How can you tell whether electrical current is flowing in a circuit? How does the brightness of bulbs compare in series

and parallel circuits? What happens to the flow of electrical current if you take a bulb out of parallel or series circuits? Which would wear out first—a battery in a series circuit or a battery in parallel circuits?

Because students differed in their ideas about the flow of electrical current, making their thinking known and listening to the reasoning of others was important in forming a model. For example, when asked to predict which battery would wear out first—one in a series circuit with three bulbs or one in parallel circuits with three bulbs—students did not agree in their predictions. Some were confident in their choices and were anxious to explain their reasoning while others were unsure. By the end of discussion, most students agreed correctly that the battery in parallel circuits would wear out first. Here is part of a class discussion representing the viewpoints and reasoning of the students.

Teacher: Which do you think would wear out first?

Student 1: Probably the series one.

Teacher: Why did you choose the series one?

Student 1: Because one circuit is going through three light bulbs and trying to get power to all three light bulbs with one battery.

Teacher: I see a lot of hands up. What do you think, Student 2?

Student 2: The parallel ones because it's brighter and it's charging more energy.

Teacher: So you think this one will wear out first (pointing to parallel circuits). And what do you think Student 3?

Student 3: I think it's parallel because it has to share enough for everybody and it has to go in all these different wires and some of the wires use up a little bit more energy just to make them so they can work—like water: sometimes it gets stuck on rocks; it doesn't always keep on going—it sometimes gets stuck on a rock when the river dries up.

Teacher: And how are you comparing that to the light bulb, Student 3?

Student 3: Some of the energy might wear off because it's going in all these different directions. And with the series it just goes all in one complete motion instead of splitting like in parallel.

Student 4: The parallel one would wear out faster because the battery only has so much energy and it gives it out to three wires.

Student 5: In series it only has to go one place and in parallel it has to go to three different places so I think parallel would wear out first.

Whether the ideas students are developing are about electrical energy or in another context, opportunities for students to communicate their viewpoints and reasoning are important to their conceptual development. These opportunities also provide windows to the thinking of students and help teachers to assess how the understanding that the students are developing compares with that of the scientific community.

ENDNOTES

1. Development of this case study was partially funded by a grant from the National Science Foundation (MDR-9155726) to Dr. Emily H. van Zee. Opinions expressed are those of the author and do not necessarily represent those of the funding agency.
2. This paper was presented at a workshop, "Teachers as Researchers: Studies of Student and Teacher Questions During Inquiry-Based Science Instruction," at the 1997 annual meeting of the American Association for the Advancement of Science in Seattle.

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Science Inquiry Conference—A Better Way!¹

Diantha Lay

“Inquiry into authentic questions generated from student experiences is the central strategy for teaching science,” according to the *National Science Education Standards* (National Research Council, 1996, p. 31). As a fourth-grade teacher, I want my students to generate their own questions about some aspect of science and develop projects based on these questions. Then they discuss their projects with other students in our school during our Science Share and with students from other schools during an inquiry conference (Pearce, 1993; Bourne, 1996). Inquiry conferences are a better way to celebrate student learning because they involve the students in talking with one another about what they did rather than being judged by adults as is typical in traditional science fairs.

Preparing for an inquiry conference is a long-term process. Throughout the year, we keep a class list of things we wonder about as we move through the various science units. Among the questions my students have generated this year are “Why do big fish sometimes eat little fish?” “Why are minerals valuable and rocks aren’t?” “Is lightning electricity?” “Are kids’ reflexes faster than adults’?”

When the time comes to develop projects, we begin by looking at our list of questions. It is important to me that the students develop projects in which they have a vested interest. Research has suggested that projects are more meaningful

if they are developed out of the interest of the children, rather than the design of the teacher (Katz & Chard, 1989).

The projects provide an excellent opportunity for an extended writing activity that takes the students through the entire process of writing, editing, rewriting, and publishing. First I ask the students to write to me about questions that they have. The questions should be based on something they already know that allows for further exploration. One student, for example, wrote about the purpose of a study of bubbles, "To find out what holds bubbles together by experimenting with a variety of solutions. I want to find out what causes the colors in bubbles. I also want to find out which solution makes the biggest and most colorful bubbles." Then we write back and forth in journals about the questions. I wrote back to this student, for example, "Can you take pictures? Can you compare colors? How? Sounds good!"

We also have conferences about the students' questions. I try to direct their questions to more meaningful topics beyond what we have done in class. One of the questions that a fourth grader wanted to explore, for example, was "Will oil and water mix?" As I remember our conversation, I asked, "Do you know the answer to that question?" The student said, "It's something I wonder about." I responded, "What do you wonder?" The student said, "Why don't oil and water mix?" and I said, "OK but do they mix?" "No, they don't mix" was the answer and I replied, "So your question is really not 'do they mix?' but 'why don't they mix?'" Sometimes my students need help getting focused on what their questions really are. They know they have some kind of question about a topic but they need to figure out what they are really wondering.

The students keep journals of the progress they are making. A progress report contains information regarding their research up to that point. I want to be sure that all students are working on their projects and to follow up on students who may be falling behind. After the students have formulated their questions, the next task is to list all of the materials they need for the research. They also have to explain how they plan to find the answers to their questions. Here is an example progress report:

This week I got all my materials ready. For the past few days I was thinking when I would start my project, and I decided Thursday night. Today I started. I was unable to get strawberry juice so I decided to use coconut juice. Tonight I tested punch and orange. First, I got both juice in a cup and then two shiny pennies (keep on reading to see why). After that I went outside to my front yard and there is a faucet. So, I turned

on the faucet and let the water run on the dirt. Then I put dirt on both pennies. After I did that I put the dirty pennies in the punch and orange juice (one in each cup). I let sit for a while. When I looked at it and moved it with a toothpick and got the pennies out with my hand! Disgusting! Then I dried them. So far I think punch cleans a penny the most. But I have two more juices to test! I mean lemonade! What a long progress report!!

I responded to this student, “Great job! Leave it there for a few days and see what happens! What do you predict?”

The next step is to experiment and explore the students’ questions to see if they can come up with answers. Then they draw conclusions based on what they find with their experiments. The students edit their own reports. Then I edit the writing pieces and return them to the students. After they write the final reports, they present their projects to the class.

The students also have an opportunity to assess their own work in the form of a rubric. They develop the rubric with my help and assess their own work and one another’s. The rubric for the science projects had several parts: a point for the scientific process; two points for the scientific process and what you learned; three points for the scientific process, what you learned, and a comparison of your results with what you thought was going to happen (your predictions). To get four points, you had to include all that plus a reflective piece on what you would do differently if you were doing this over again—what went right, what went wrong, and if you were going to do the project again, what changes you would make.

Traditionally the big emphasis has been on the scientific process and making sure each of those steps is labeled properly on a display board. I wanted to change that. Students can go through the scientific process and still not really be engaged in reflective thinking about what they have done. They can have results and draw conclusions but not really think about the meaning of what they have done. So many think that they can run a test one time and that gives the answer. By presenting their projects to one another, the students learned to become more critical thinkers, not just with their own project but in evaluating their peers’ work as well. The students gave their rubric sheet to one another, not to me. There was a place on the rubric sheet for comments and even the kids who got two’s were thrilled to have a whole pile of papers with comments. They sat there and read them. It was a learning tool for them. This was private, for their own information, for them to learn and to give them some ideas about what they could do.

Someone might say, for example, “I wish you had spoken louder because you had good things to say.”

At the Science Share at my school this year, projects were set up in individual rooms instead of one large place. There was a certain period of time when students would be at their projects to answer questions as people came through. No judging occurred but everyone who participated received a certificate of participation.

After reading Barbara Bourne’s description of a Kid’s Inquiry Conference (1996), I became interested in organizing one. Also I attended a seminar about these conferences and saw their value and benefits. As a participant in the Science Inquiry Group, I was able to convince its sponsor, Emily van Zee (1998a), and two of the other teachers to work with me. After a great deal of planning and preparation, sixty-five students in third through fifth grade came to the University of Maryland to participate in the conference.

The students discussed their projects with one another in small groups and then shared what they had learned in a large group discussion. They also evaluated the conference. They said that it was very helpful having as much time as you needed to talk about your project and to share with other people and be able to answer questions. At school, they had had to tell everything in a minute and a half. They thought it was helpful to be involved in talking with students besides those in their own schools. They said that presenting to people who do not know you is different because sometimes people you are with every day do not take you seriously. As part of this closing discussion, I asked what the students would say to teachers about learning science. They said that teachers hand out too many worksheets, don’t do enough science, don’t wait and let the students find out the answers, and tell the answers before class is over, and that the hands-on part of science is the best part.

The inquiry conference was one of the highlights of my teaching career. It was so powerful to be a part of all of the sharing and to watch the students talk about their projects, to have the confidence and ability to stand up and talk about what they were doing—just a remarkable growth experience for those students, something they’ll remember for the rest of their lives. As we were leaving, two college girls got mixed in with our group. One said to the other, “Did you ever visit a college when you were in elementary school?” The other said, “No way! What are these kids doing here? Isn’t that cool?” I answered, “Because they had fabulous science questions that they came here to share with the world!”

ENDNOTE

1. Development of this case study was partially supported by a grant from the Spencer Foundation Practitioner Research: Mentoring and Communication Program to Dr. Emily H. van Zee. Opinions expressed are those of the author and do not necessarily represent those of the funding agency.

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Science Beyond Labeling¹

Rhonda Hawkins

Science, reading, and writing are nearly inseparable. In my sixth-grade classroom, I have three students who are considered resource students. They carry labels that have reinforced their conviction that they are poor readers, writers, and students in general. As the science teacher, I have seen these students conduct experiments with their peers and do just as well. When the hands-on activity is completed, however, and the reading and writing portions of the experiment must be tackled, the labels resume the mystical tyranny over their abilities. In this case study, I have documented their conversations during the experimental process and provided accommodations in reading and writing. In the course of closing the disparity between their ability to participate in the hands-on task and their ability to translate that into print, I have explored ways in which these students can use the field of science to piece together the web of reading, writing, activity, and understanding. Data collection included audiotapes of conversations within the students' groups during an experiment and experimental write-up with accommodations that included textual readings by the teacher or among the three, summarization of main points, questionings by the teacher, and her transcription of answers dictated by the students.

My school is in a suburban area mostly of white-collar workers. There are thirty-three students in my sixth-grade class, eighteen boys and fifteen girls, most

of whom are reading on a fifth- or sixth-grade level. The two boys and one girl in this study have not been held back but each receives services in reading as part of an Individualized Education Plan (IEP). The names are pseudonyms.

Noah is the most outspoken of the three students. An African American with diverse interests, Noah is not afraid to take risks. When asked to read or write in front of the class he does not hesitate. He makes an attempt and is willing to accept help from his classmates and his teacher. In describing how he had worked on a task in a small group, for example, he pointed out one of the parts that he had read and at what point he had someone else read for him. From his own admission, he is a poor reader but his ability to comprehend the processes of science and have a plethora of questions is not affected. The difficulty comes into play when he is unable to make basic connections between his mental processing of information and what is in printed text. When he does not understand something, he will ask questions of his teacher and classmates.

Caleb is an African-American student, often troubled by something. As a member of the class, he is quiet most of the time, hoping to go unnoticed. When he is called upon, he responds sheepishly, yet with my help he will come up with an answer. When working with his classmates, Caleb relies heavily upon them to do all of the work and to explain to him what is being done. I use discretion in pushing him so that he will remain a part of the working group and maintain some responsibility and ownership for the task being completed. Believing that he cannot do anything well, he attempts to do as little as possible. One-on-one Caleb is like another person. He works hard at solving problems and is attentive to what you say. A part of him remains withdrawn but he is willing to work in a small setting.

Michaila is an African-American female who is very outspoken and confident. She prefers to do things on her own and often gets offended if you make her feel as though she cannot read or do something her peers are doing. Even though she may need assistance, she will not admit it. As a working member of her cooperative group, Michaila is just as aggressive as the other students. When she is wrong, she plays it down and picks up in another part of the task. Because of the pull-out demands of her special education program, she is very sensitive to being singled out. When given the choice, Michaila prefers to stay with her peers and fit in. In private sessions Michaila is responsive as long as she does not feel as though she is in a remedial setting.

The teacher is an African-American female with five years of teaching experience. I am the teacher and researcher referred to in this study. You may notice that in expressing personal experience I refer to myself in the first person while

in speaking objectively I employ the third. For four of the five years that I have been teaching, I have taught science for at least part of the year.

My strengths are discipline and organization. In order for me to have an organized classroom setting, my students must be comfortable and in agreement with how our class is run. One of the major difficulties for me is breaking organization for the sake of student inquiry. In my day-to-day assessment of how I am doing in relation to my students' needs, adapting and adjusting to their demands is a big consideration for me. One thing I do well is the dramatics that I engage in when teaching and interacting with the students. This manner of reacting and relating to my students establishes a rapport that transcends textbooks and traditional relationships between teacher and student. As a learner, I am always emerging into another state of comprehending. When I am teaching I learn as much as my students do. The biggest difference between my students and me is that I am responsible for organizing and presenting material in a way that will benefit all of them. I enjoy teaching, learning, and interacting with the students but I would be remiss if I did not admit to great frustration with constraints such as large class size, disjointed curriculum demands, administrative overloads, and unrealistic time allotments.

In my sixth-grade classroom that includes Michaila, Noah, and Caleb, inquiry learning and teaching centers on questioning by students and teacher. The students' search is within the context of science as it relates to their natural interests and prior knowledge. Mine is within the context of finding the best means of helping my students learn the content of science and apply the skills of scientific investigation to other areas of their learning. The teacher must also make sure that the students' inquiry is not hindered but capitalized upon, while at the same time guiding their inquiry so that it is directed enough to meet the requirements mandated by the state, county, and whoever else has some say as to what the students must know. By context, I refer to where the teacher or the student makes meaning of circumstances and conditions. Within the classroom, students are naturally inquisitive and this inquisitiveness is grounded within their context. Inquisitiveness can often lead to further exploration and enthusiasm in science investigations. Allowing students actively to engage in questioning, exploring, and refining their inquiry through reexamining their original question makes for both learning and teaching (National Research Council, 1996, p 31). The result is contrary to much that emerges within the school curriculum and traditional classroom instruction. That applies to my three special students along with the rest of the class.

All Maryland elementary schools put a great emphasis upon the Maryland School Performance Assessment Program (MSPAP), which drives instruction

toward specific outcomes. In science, this program fosters hands-on science; there are tasks designed specifically for meeting the science outcomes and performance standards as designed by the Maryland State Board of Education. Using these guidelines, my students and I continually work on tasks that explore a topic in one of the science disciplines. These tasks not only concentrate on the content but are embedded with the skills needed to conduct scientific investigations (graphing, labeling, diagramming, identifying variables, predicting, and so forth).

Very often my students are so curious about the content of a MSPAP task that they attempt to rush through conducting a scientific investigation. For example, my students worked on a task involving chemical reactions and fair testing. Using Alka-Seltzer as the catalyst, the students went through two initial investigations to explore the basic components of chemical reactions and to expose them to going through the steps of a scientific investigation as a means of answering a question. The culminating task was to design their own investigation from hypothesis to conclusion, utilizing all the materials on a designated list. In all three classes, each with eight groups, the students were so fascinated with mixing chemicals that they completely disregarded controlling variables. At the end of the investigation, we had cups of liquids mixed with Alka-Seltzer and reaction times that varied with no apparent reason. After scoring the task as a class, we discussed the findings of the investigations and the implications upon conducting the fair tests.

Throughout this investigation much more was going on than a search and findings. For my students, there was an excitement that accompanied the freedom to investigate chemical reactions. Even though they had agreed to collect data on specific chemical reactions, every group failed to resist the temptation to mix several chemicals and then collect data on the reaction time and observed reactions. All of my groups collected data and formulated some way to show these through graphing or charts. Their inquisitiveness and the excitement of having the freedom to investigate caused them to formulate several questions at one time. It is at this height of excitement that I, as the facilitator, stepped in and attempted to guide their questions in some type of logical pattern to answer the questions they had put forth as well as those to meet the task requirements.

For the teacher, completing a task of this sort with students can be arduous. Their questions and the speed at which they generate them is enough to tire even the most hearty of science teachers. But the questions are the catalyst of opportunity to foster science attitudes and investigations that lead to a lifetime of learning. I often find myself choosing which to address, content or process.

As a means of meeting the demands of MSPAP, I continually assess and choose what needs to be emphasized and what can be revisited in other investigations. When my students had completed their investigations with chemical reactions, for example, we had such a mix of uncontrolled data that I chose to emphasize how they record the information that they collect. The one thing that is not negotiable is the factor of student inquiry. If they do not engage in inquiry through the questioning and challenging of what is being presented, then I do not have strong basis for holding and refining their attention to whatever task we are doing.

The written work of my three special needs students during the Alka-Seltzer investigation gave very little evidence of comprehension of the directions and the demands of the task. The written data reflected the students' lack of ability to translate text into their own written text. Students who have difficulty in this will meet with little success when science tasks rely heavily upon reading and not doing (Mastropieri & Scruggs, 1994; Scruggs et al., 1993). The portions of the task that the three completed had been with the help of group members. The pattern of their writing followed the ease with which a group member could commit time to assisting them with directions or writing.

Before repeating the first portion of the task, I explained to them that to understand what they did and did not understand, I needed their help. We also talked about how they felt about reading and writing. We looked at the text included in the task and they agreed that it was a lot and they expressed relief at not having to read all of it. When I explained that they would not be writing answers, they expressed their appreciation with a smile and even more enthusiasm towards completing the task. To make it as equitable as possible I allowed them to call out answers. When one person dominated the conversation or answered most of the questions first, I would call on one or the other to respond first so that answers would not be influenced by what others had said.

The responses to the task demands were very accurate and insightful, and would have resulted in a satisfactory if the three had been able to write them as well as they could say them. An example of their dialogue is shown in Table 1. They knew the purpose of the experiment (line 2), reflected upon the results (lines 7-8, 10-11), formulated new questions (line 12), and made predictions (lines 14-15). As for specific task behaviors, when it came to controlling variables in later parts of the investigation, these students reacted the same way the rest of the class had. They were so eager to mix chemicals that controlling the experiment was the last thing on their minds. Inquiry was winning over scientific process.

TABLE 1. DIALOGUE ABOUT THE ALKA-SELTZER EXPERIMENT

Before the students conduct the tests:

1. **Teacher:** When we conduct this experiment what are we looking for?
2. **Michaila:** How long it takes for the Alka-Seltzer to melt.
3. **Teacher:** Okay. What is another scientific way to say melt?
4. **Caleb:** Dissolve.
5. **Teacher:** Great. Timekeeper, are you ready? Don't forget to record your data on the data table.

After they conduct the tests:

6. **Caleb:** I told you the hot water would melt it quicker.
 7. **Michaila:** The hot water dissolved it quicker.
 8. **Teacher:** What are you talking about?
 9. **Noah:** The hot water made the Alka-Seltzer dissolve faster because it was so hot.
 10. **Michaila:** The cold water was the slowest because it slows down the reaction time.
 11. **Caleb:** I wonder what would happen if you used hot water to dissolve other stuff?
 12. **Teacher:** If we changed the size of the tablet will that affect the dissolving time?
 13. **Noah:** Yeah. The less there is to melt, the faster it will melt. Dissolve.
 14. **Michaila:** It would probably take a long time for a whole box of tablets to dissolve.
 15. **Teacher:** When we change things on purpose in an experiment what is that called?
 16. **Noah:** Variables?
 17. **Caleb:** Independent variables. We changed the temperature of the water on purpose.
-

I plan to experiment further with having these students tape their answers. Then as a small group we can transcribe them with word processors. Approaching tasks and their learning this way may enable me to hold their

attention and begin to bridge the gap between their facility in experimentation and their abilities in reading, writing, and processing text. When we worked in a small group with other students on or near their level, they appeared to be more comfortable and willing to take some risks. To improve in reading and writing, they have to take a lot of risks.

My three students need many things, some basic some complex. The basic needs include personal attention directly to address their problems in learning, compassion and understanding for their current level of accomplishment, and time to grow and process things that we take for granted other students know at this level of learning.

ENDNOTE

1. Development of this case study was partially supported by a grant from the Spencer Foundation Practitioner Research: Mentoring and Communication Program to Dr. Emily H. van Zee. Opinions expressed are those of the author and do not necessarily represent those of the funding agency.

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Collaborative Conversations: Strategies for Engaging Students in Productive Dialogues^{1,2,3}

Dorothy Simpson

Many years ago the idea of discussing concepts with students in a mathematics context was presented at a workshop I attended. Since then I have continually tried to improve upon the process of letting my physics students develop their own ideas to reach a logical conclusion.

I believe this is a great method for helping students talk about their ideas, develop them logically, and reach some understanding of the process of science and the way real scientists work. These classroom discussions certainly fit the requirements for focusing and supporting inquiries, orchestrating discourse, challenging students, and encouraging and modeling skills of scientific inquiry as listed in Teaching Standard B of the *National Science Education Standards* (National Research Council [NRC], 1996, p. 32).

The teacher's role in orchestrating discourse, according to the *Standards*, "is to listen, encourage broad participation, and judge how to guide discussion—determining ideas to follow, ideas to question, information to provide, and connections to make" (NRC, 1996, p. 36).

Such discourse is very different from a lecture in which a teacher explains physics principles and demonstrates ways to solve physics problems. Such discourse also differs from a recitation in which a teacher asks *students* to explain

physics principles and demonstrate ways to solve physics problems. Such discourse involves reflection, not only on what one knows but also how one knows something and why one believes that to be the case (Minstrell, 1989; van Zee & Minstrell, 1997).

IDEAS FOR DIALOGUE

The following presents my strategies for encouraging dialogue with students, from eliciting preconceptions to bringing closure to a unit. These strategies might provide a point of departure for teachers embarking on this approach for the first time or some insights for teachers more experienced with this approach to teaching.

The structure of a unit is shown in Table 1. For students to develop “big ideas” through dialogue, they need to start with a familiar situation to which they can relate. The situation should take the form of a pre-instructional exploration activity that encourages students to explore relevant physics ideas.

TABLE 1. STRUCTURE OF UNIT

Pre-instruction (exploration) activity
Present situation from which to elicit student preconceptions
Dialogue about exploration
Open out dialogue—many possibilities
Develop hypothesis
Development activities
Look for questions about situation
Look for inferences to support observations
Dialogue about development activities
Start closing
Reexamine pre-instruction ideas
Analyze for logic, consistency, validity, and reasonableness
Dialogue for closure
Foster logical evolution of ideas toward thinking of physicist

A dialogue about the exploration activity encourages further thought and curiosity about the physics involved. After this dialogue, students work on developing the concepts through demonstrations and activities in a logical sequence. Small-group discussions provide the basis for class development of the big ideas related to the unit. The small groups present their ideas to the rest of the class, and then there is a dialogue about the development activities in which students introduce evidence to support or refute each idea. The class narrows the list as the students reach logical conclusions about each idea.

The teacher-mediated discussions lead to closure as the students use logical reasoning about the observations to establish inferences that physicists would consider acceptable. During discussions I use the strategies presented in Table 2. I specifically discuss with students my expectation that they will improve or develop the skill of asking good questions by considering the implications of the points listed in Table 3.

TABLE 2. STRATEGIES FOR TEACHERS DURING A DIALOGUE

Are you inviting all students to speak without judging their comments?

When opening a discussion, are you refraining from commenting on student ideas and remaining ambiguous regarding your own ideas?

Have you listed ideas on a board or overhead projector before discussion?

Do you ask for supporting evidence for each comment after all are elicited?

Do you ask questions to help the student construct a logical conclusion?

Do you refrain from “telling” the student the pieces he or she is struggling to construct?

Do you paraphrase each comment?

Do you validate each speaker with an acknowledging comment?

Do you provide “wait time” after a question, before allowing comments?

Do you ask for counterarguments for each idea after all ideas are elicited?

Do you ask questions that direct a student's thinking to a conclusion showing the fallacy of the argument?

TABLE 3. STUDENT STRATEGIES DURING A DIALOGUE

ACTIVE LISTENING

Do you listen carefully to what the speaker is saying?

Do you listen from the point of view of the speaker?

Do you actively consider the ideas presented?

Do you try to find a pattern in the observations and ideas of other students?

Do you mentally paraphrase what the speaker said?

Do you think of questions you could ask the speaker to clarify?

Do you think about the observations and look for missing pieces?

CONTRIBUTING

Do you indicate your desire to speak without interrupting the speaker?

Do you make comments that further the discussion about the ideas just presented?

Do you ask questions about what the speaker said?

Do you ask for clarification of what the speaker said?

Do you challenge what the speaker said, based on your evidence?

Do you refer to the ideas presented rather than to the person who introduced the ideas?

Do you try to present arguments and counterarguments to the ideas presented?

PRE-INSTRUCTIONAL EXPLORATION ACTIVITY

Pre-instructional activities create a context for student thinking by presenting some familiar situations related to the concepts in the unit. A possible exploration activity for a unit about forces might be students drawing force vectors on a diagram of the motion of a tossed ball. Discussion of the ball's motion provides a natural motivation for students to attempt to come to consensus about the forces in the situation.

I open the dialogue about the exploration activity with a discussion about any preconceived notions of the physics concepts involved. I then place ideas on the board or overhead projector for students to consider, and I invite students to give reasons from real-life observations as to why they think as they do. An example of a student idea might be that there needs to be a force on the ball in the direction of motion (McDermott, 1984); in this case students often propose that such a force would be provided by the hand. Our goal is to help students apply their understanding that hands cannot exert a pushing force if they are not touching the object.

Possible questions for the dialogue about the exploration activity include:

- ▶ What do you think might happen?
- ▶ What experiences have you had to support your idea?
- ▶ Does that always happen?
- ▶ What might be some reasons why _____ would not happen?
- ▶ What other possibilities might you suggest?
- ▶ Who has a different idea about what might be happening?

As students discuss their ideas, they try to create logical arguments and develop tentative hypotheses. Helping students focus on what they believe stimulates their thinking and gives them a starting point from which to compare observations and final inferences. During this discussion students consider evidence for counterarguments. They also revisit concepts such as forces touching and forces at a distance.

DEVELOPMENT ACTIVITIES

Development activities engage students in examining their ideas further with demonstrations or hands-on experiments. Students record and discuss observations within lab groups. During these activities they ask questions about what is happening and continue to consider their predictions. They might think of

related situations and form additional “What if...” questions and then develop their own experiments to test their hypotheses. During this phase of the unit, students develop ideas to present as suggested “big ideas” from their group.

During the dialogue about the development activities, students elaborate and develop their ideas by reviewing the observations from the development activities. It is important that the observations be accurate enough that students can make valid deductions about the concepts. For example, students can move dynamics carts on a frictionless track and observe that they tend to continue at a constant velocity. At least one student will remember Newton’s law of inertia and apply it to this situation, which is similar to that in which a ball is thrown horizontally. This result is in contrast to the students’ initial hypothesis. By discussing the ideas from all lab groups more information is presented for finding patterns.

In a dialogue about the remembered ideas and the pattern that is formed, students develop their ideas and follow their reasoning to a logical inference. This discussion helps students move from observations to inferences using logical arguments to reach logical conclusions. They consider how valid their inferences are and the reasonableness of their conclusions. The comparison of the predictions from the exploration activity with the experimental observations is a critical part of the process of leading students to understand the concepts. The contrast between what students expect and what they observe or conclude is often an “aha” experience that helps them to mesh their original ideas with the logic of the conclusions.

Possible questions for dialogue about the development activity include:

- ▶ What is your evidence for that idea?
- ▶ What was your observation?
- ▶ What might you infer from that observation?

DIALOGUE FOR CLOSURE

I move toward closure by asking a variety of checking questions and carefully observing students’ nonverbal expressions. Many ideas have been tossed about, and some students may have become confused with all the possibilities. Some students may have tuned out from active thinking about the inferences.

As the dialogue about the observations and inferences reaches a conclusion, it is important for the teacher to ask if the students agree about the conclusion. The agreed upon conclusion needs to be repeated several times in several ways

so all students understand it and can mentally agree with it. If any students still have questions, it might be necessary to reopen the discussion with some pertinent points of the logical sequence from observation to big idea to help the doubting students follow the logic.

GENERAL COMMENTS ABOUT QUESTIONS

When teachers start using this process to help students think critically about the predictions, observations, and inferences, the dialogues usually tend to be dominated by teacher questions with student responses. As students become accustomed to the process and as they practice logical thinking and mental debate of the ideas, they will start asking questions. The student questions need to be answered with a teacher question that helps them move along in the logical reasoning.

As the process evolves, other students will become involved and some of the best reasoning dialogues will involve students only, bypassing the teacher entirely. This is a very valuable learning situation in which students talk and reason with each other. They are actively thinking and have matured in their ability to reason logically so they can move to conclusions without the crutch that the teacher questions provide.

To negotiate a dialogue of logical thinking leading to physics big ideas, the teacher needs to use a variety of techniques. Guiding the discussion requires a great deal of focus to listen and process the comments. Before a dialogue of this kind can occur, a safe atmosphere must have been created so each student feels free to take a risk and make a statement without fear that it might be wrong. Students should be reminded that there are no right or wrong statements in these dialogues.

Choices must be made by the teacher as to the direction of the dialogue. Is this a comment that requires more probing? Is this a comment that helps the group move to the big ideas? Is this a comment that leads to a tangential idea and needs to be postponed for another day? If this is a comment that might lead the class astray or add confusion, what question will help direct the conversation back to the big idea or help a student redirect his or her thinking? Is this a dialogue to open up the student ideas, a dialogue to consider observations and inferences, or a dialogue for closure, culminating with the big ideas?

Negotiating dialogues in this way requires much work by the teacher, who always strives to maintain the direction of the discussion, but the payoff is understanding gained by students.

ENDNOTES

1. This article is reprinted with permission from NSTA publications, copyright 1997 from *The Science Teacher*, National Science Teachers Association, 1840 Wilson Blvd., Arlington, VA 22201-3000.
2. Preparation of this manuscript was partially funded by grants to Jim Minstrell and Earl Hunt by the James S. McDonnell Foundation and to Emily van Zee by the National Science Foundation (MDR 91-55726). Opinions expressed are those of the author and do not necessarily represent those of the funding agencies
3. This paper was presented at a workshop, "Teachers as Researchers: Studies of Student and Teacher Questions During Inquiry-Based Science Instruction," at the 1997 annual meeting of the American Association for the Advancement of Science in Seattle.

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Teacher Inquiry¹

David Hammer

INTRODUCTION

To think of inquiry in the classroom is almost always to think of student inquiry. One does not often associate inquiry with the teacher's role, other than with respect to questions that come up within the discipline, science questions for a science teacher, for which the teacher does not have an immediate answer. My first objective in this chapter is to promote a view of inquiry as central to the teacher's role, particularly inquiry into student understanding, participation, and learning.

Although it is becoming more common to think of teaching as inquiry,² the emphasis in education reform remains on methods, materials, and standards. Meanwhile, the progressive agenda of promoting student inquiry, along with the need to coordinate that agenda with the traditional one of "covering the content," places substantial intellectual demands on teachers. If these demands are not considered and addressed, the progressive agenda is unlikely to succeed. In other words, to pursue science education reform through the development of new curricula, new materials, or new standards is not sufficient. To promote student inquiry, we must do more to understand and support teacher inquiry.

To begin, teachers spend a significant portion of their days taking in and interpreting information about their students. Much of this data gathering is deliberate and explicit: taking attendance, collecting homework assignments and laboratory reports, giving quizzes and exams. Other information arrives on its own, in a nearly continuous stream, in the questions students ask and comments they make as well as in their facial expressions, body language, tone of voice. It is an enormous amount of information.

How teachers interpret that information, what they perceive in their students (whether the students are paying attention, confused, interested, frustrated, etc.) can dramatically influence how they choose to proceed (pose a challenging question, provide information, continue to new material, digress to pursue a student's idea). Most of this interpretation happens—must happen—automatically. In this respect teachers are like other practitioners, from professional chess players to doctors, whose judgments are and must be largely tacit.³

Regarding chess players and doctors, however, there is a general awareness that this perception and judgment is taking place, that it is intellectually demanding, and that its betterment is central to professional education. It is both possible and expected for chess players and doctors to make at least some of their reasoning explicit, as a matter of professional practice and development, and they do so in the contexts of specific games and cases. For teachers, in contrast, it is rare to have the opportunity, let alone the expectation, to present information from their classes to others, to make explicit their interpretations, or to consider alternatives.

CONVERSATIONS AMONG TEACHERS

This chapter describes work from a project designed to engage teachers in precisely this sort of conversation, centered on their ongoing experiences in the classroom. From March 1995 through June 1998, a group of physics teachers and I met every other week of the school year for two hours, to talk about students and teaching. Our conversations, recorded on videotape for transcription and analysis, focused on snippets from the teachers' classes, small samplings of the information they were taking in about their students, in the form of transcripts, video or audiotape recordings, or samples of students' written work. Reading, watching, and listening to these snippets, we talked about what there was to see in the students' participation, exploring a range of possible interpretations. The teachers in the group and their school affiliations during the 1996-1997 school year were: Elisabeth Angus, Winchester High School; Hilda Bachrach, Dana Hall School; Edmund Hazzard, Bromfield School; Bruce Novak, Watertown High

School; John Samp, Cambridge Rindge and Latin High School; and Robert Stern, Brookline High School.⁴

This chapter is organized around excerpts from three of our conversations along with the classroom snippets they concerned that were contributed by Robert, Hilda, and Bruce. These conversations, from three consecutive meetings in the fall of 1996, are representative of the substance and tenor of our work. They also reflect a range of physics topics and types of snippet. I will use these examples to advance three objectives:

- 1) **Teacher perception and judgment.** The first, as I noted above, is to promote greater appreciation for the role and demands of teachers' inquiry into their students' understanding, participation, and learning.
- 2) **A language of action.** The second is to offer an insight that has emerged from our work regarding the language teachers use to express what they find in that inquiry. In our conversations, the teachers often experienced and communicated their interpretations in a language of action, in other words as ideas for what to do in the given circumstance, rather than in an explicit language of diagnosis. For a simple example, a teacher may express an interpretation ("The students have forgotten what they learned about inertia") by suggesting an action ("I would review the concept of inertia").
- 3) **A role for education research.** My third objective is to propose a view of the role of education research in instructional practice. Specifically, I will suggest that its primary role is to contribute to teacher inquiry, to teachers' perceptions of their students and judgments for how to proceed, rather than to prescribe effective methods. The conversation between teachers and researchers should therefore be understood to take place mainly at the level of their respective interpretations of students' understanding and participation. This conversation, however, may be difficult to recognize and to facilitate, owing largely to differences in the language by which researchers and teachers experience and communicate their interpretations.

INTERPRETING A CLASS DISCUSSION ABOUT FREE FALL: TEACHER INQUIRY INTO STUDENT UNDERSTANDING AND PARTICIPATION

The first snippet we discussed in our meeting on November 18, 1996 was a transcript Robert had prepared of a discussion in his college prep class⁵ about the forces on a skydiver. Robert wrote in the snippet that his goal for this activity had been “to reinforce the idea of the net force as the driving engine for acceleration.” Here is roughly half of the transcript.

Teacher: What forces act on the skydiver when he first jumps out?

Student 1: He accelerates down; he goes faster.

Student 2: But the air slows him down so he can't fall faster.

Student 3: But he doesn't slow down so something must be getting bigger.

Teacher: Someone come up to the board and draw the forces acting on him.

Student 4: There's the gravity that pulls him down. (Student draws a vertical arrow down.)

Teacher: What's the common English word for force of gravity?

All Students: Weight.

Teacher: (to student 4) Add the letter W to your diagram. Now what?

Student 4: Then there's the air resistance. (He draws a vertical arrow up, but not connected to the weight arrow. Long silence.)

Student 5: You have to put the arrows together.

Teacher: Why?

Student 5: Because they're both pulling on the person.

Student 4: Yeah, that's right. (He draws both arrows connected to the same point.)

Teacher: How are the two arrows related? Are they the same? Is one bigger?

Student 4: Well, the weight is bigger because it's pulling down.

Teacher: Does everyone agree? (Calls on a student.)

Student 6: No, it can't be right because the speed is increasing. The force of gravity is getting bigger.

Teacher: What's the common word for force of gravity?

Student 6: Weight.

Teacher: So what are you saying? The person gets heavier as he falls?

Student 6: (smiling) No, but something is wrong. He keeps going faster as he falls, doesn't he?

Student 4: Sure he does but it's the gravity that pulls him down.

Student 7: But doesn't the air resistance get bigger?

Teacher: You have some good ideas, but there is confusion here. The difficulty, as I see it, is that you're confusing the MOTION with the FORCES. Remember that you started the year with learning how to describe motion (kinematics). All the graphs and equations you did. Now you're looking at FORCES (dynamics). It's the forces which make things move and we've got to separate these two effects. Let's concentrate on just the forces; then we'll connect them to the motion.

Excerpts From Our Conversation

Bruce started our conversation with the suggestion that Student 6's comments revealed a common misconception. Robert's response showed that he too considered Student 6's contribution significant, but for different reasons.⁶

Bruce: [Student 6 showed] a misconception, that we've talked about before. That the speed is proportional to the force (reading Student 6's comment from the snippet): "That can't be right because the speed is increasing. The force of gravity is getting bigger."

Robert: [Student 6] is usually very, very slow in reaching any sort of [original idea], so for her to say what she did... She said it so immediately, she knew the speed was changing, but in all of the year it's the first time I've ever seen her, you know, come up with something herself. [There] must be something else, another force, another factor. It was nice to see her do that. She couldn't quite get it, and I'm not sure whether that's [important]. I thought it was a turning point in the whole discussion.

After a brief exchange to help others locate Student 6's comments in the transcript, I turned the conversation back to what Robert had been saying.

David: And that was a turning point and the student who said that was somebody who—

Robert: Who normally doesn't see things very intuitively. She's very methodical, she's very good at memorizing stuff... But for original

ideas, no. This is the first time that I saw that with her. Which was that you can see that somewhere what we had is not enough. There needs to be something else. But you didn't know what it was.

Shortly later, Robert elaborated on what he had intended in this conversation and what he saw happening at this juncture:

Robert: I've never done this one before.... I'm using a new textbook this year and I looked around, I thought that might be a good way to tie up some of the ideas, let the students talk. Instead of doing [lots of] problems today, we'll spend a while, whatever we need, just talking about [one] problem. And it just was so enlightening to me to see that, just what you're saying, [they came up with the] idea, there needs to be another "force." That's the key item: There needs to be something else to make it accelerate. It doesn't have to be an increase in the force, but it needs to be something.

Turning back to the misconception he saw in Student 6's comment, Bruce commented on Robert's response at the end of the excerpt.

Bruce: You may reinforce [the misconception] with what you say, "it's the forces which make things move." Which makes it sound like you need the force to have the motion. Which is something a lot of us say, [although] we don't mean it that way.

This reminded Robert of a related difficulty: students' reluctance to accept a velocity as an initial condition of an object, a problem he agreed his language may aggravate.

Robert: Typically the thing that comes up, now that you mention it is, even when you have problems with things moving at a constant velocity, there are always a handful of kids, you know, they want to get that acceleration in the beginning, [thinking] "you gotta get it going," and I say "OK, now it's going."...Well, maybe I contribute to that.

Bruce recalled a suggestion John had made the previous year of a strategy for responding to this difficulty: Start with the room lights off and then turn them on after setting a ball in motion. The idea is to help students distinguish between the concept of *velocity* and that of *force* by focusing their attention on the ball's initial *motion*—when the lights come on the ball is moving—and away from any prior, initiating *force*.

Hilda reminded us that the students had been talking about a skydiver, who had no initial downward velocity. In this case, she noted, the students' reasoning may have been appropriate, because "there had to be a force, otherwise [the skydiver] wouldn't come down." Robert maintained, nevertheless, that the students had not distinguished force as causing velocity from force as causing *acceleration*.

After a brief digression on the sensitivity of students' understanding to particular wording, I asked Robert to say more about the snippet. He reflected on his impressions of the discussion, reiterating his pleasure and surprise at how it had gone, and recounted more of what had happened in the class after the segment he transcribed.

Robert: I thought it was a great class. The class ended, the kids didn't want to go! . . . I had no idea it would turn out this way. I started out with, here's this problem, let's look at the different forces, maybe get to the idea of seeing that the net force would keep changing.

Lis: Were you drawing on the board at all?

Robert. Very little, I did very little.

Hilda: The kids did [draw on the board].

Robert: The kids did most of it. At the very end, when this one student wanted to know how—we finally got the idea that the net force is changing—he wanted to know how does the net force change? I asked "what do you think would happen?" and [he drew] a set of axes with force and time. And he stood there a while, and eventually he drew a straight line decreasing to zero. Which was, I thought, a very good first step, because the kids have never done this before.

The student was correct that the net force on the skydiver would decrease to zero: As the skydiver's velocity increases, the force of the air resistance increases as well, until the force of air resistance (upward) equals that of the earth's gravity (downward). The straight line was not correct: The net force would approach zero asymptotically, not as a linear function. Robert was impressed by the student's having made the first realization; he was not worried that the explanation should be fully correct at this point when the students were first considering the question.

Teacher Perceptions of Students' Understanding and Participation

The snippet continued further, as did our conversation; we spent roughly half an hour talking about it, the amount of time we typically allocate for a snippet. Our conversation was also typical in the range of perceptions it reflected in the snippet's author and in the rest of the group. Among their interpretations of the students' understanding and participation, Robert and the other teachers noted:

- ▶ a misconception, on the part of Student 6, “that the speed is proportional to the force.”** Bruce mentioned this in our conversation, but Robert had evidently seen something similar in Student 6's contribution, since, a moment later in the snippet, he tells the students, “The difficulty, as I see it, is that you're confusing the MOTION with the FORCES.”
- ▶ an original contribution by a student, Student 6, who was more inclined to memorization.** Robert recognized the same misconception Bruce did, but he perceived Student 6's idea in several other ways as well. He saw Student 6 as participating in a way that was new for her, a perception not available to the rest of us from the snippet itself, since it depended on Robert's experience from the start of the year.
- ▶ a valid insight in Student 6's idea that “there needs to be something else,” and a productive turning point in the class discussion.** In addition to seeing Student 6's reasoning as reflecting a misconception—that is, a conception inconsistent with the Newtonian understanding he wanted students to develop—Robert saw it as containing an insight that could help her and the class progress toward that understanding.
- ▶ the misconception as possibly reinforced, inadvertently, by the explanation, “it's the forces which make things move.”** This was not, directly, a perception of the students' understanding, although indirectly it attends to how they might reasonably interpret a statement by the teacher.
- ▶ students' difficulty with the idea of an initial velocity.** Bruce and Robert had been talking about the students' confusing the concept of motion with that of force, both with respect to this particular situation and as a more general misconception. Here, Robert connected their reasoning to a related pattern he had seen, that of students' difficulty thinking of an object as having an initial velocity.

- **students' interest, engagement.** Robert was enthusiastic about the outcome of the discussion, both for the students' engagement ("The class ended; the kids didn't want to go!") and for the substantive progress they initiated ("The kids did most of it").

To be clear, the point here is not these particular perceptions, and I am not claiming they are correct. To be sure, I expect other teachers would offer different interpretations, as happened routinely in our conversations. My point is that these perceptions represent multiple dimensions of teacher awareness concerning the students' conceptions of forces and motion, their modes of reasoning and participation, the level of their interest and engagement. It is awareness of individual students and of the class as a whole, in general, over the school year, and in particular moments.

In fact, this list of teacher perceptions is incomplete, as it reflects only those Robert and the rest of the group made explicit. Much, it is clear, always goes unsaid in our conversations about snippets. For instance, Robert saw something in the students' reasoning that led him to press them with respect to vocabulary: "What's the common English word for 'force of gravity'?" It is a reasonable guess that he saw the students' distinguishing as two ideas (the *weight* of an object and the *force of gravity* on that object by the earth) what a physicist considers one idea. By insisting on their use of the "common English word," he was insisting that they apply their everyday understanding of weight—in particular that the weight of an object is independent of its motion—to their reasoning about "force of gravity." From Robert's comments on other occasions, it is likely as well that he perceived and hoped to address a general pattern of students' treating physics as disconnected from their everyday experience. Moreover, this is only an excerpt of Robert's snippet, which itself represents only a fraction of what transpired in a single period from a single school day.

Here, then, is a first illustration of this chapter's opening premise: Teachers take in and process an enormous amount of information about their students' understanding and participation. Most of this inquiry is and must be tacit: There is more information than explicit thought could accommodate. No teacher could articulate every perception and intention.

Still, it seems to be both possible and productive for teachers to articulate *some* of their perceptions and intentions. Nevertheless, at least in the United States, it is rare for this to occur. Teachers seldom have the opportunity or occasion to show others their "data," to present their interpretations, and to have those

interpretations challenged with alternatives. Because of this, teachers are mostly left to themselves to develop the intellectual resources they need to meet the demands of interpreting their students' understanding and participation, diagnosing their strengths and needs, and making judgments for how to proceed.

We did not pretend that our conversations captured more than a fraction of teacher thinking. However, by capturing that fraction, they allowed the teachers to exchange and compare not only methods and materials but perceptions of students in particular moments of instruction. Our conversations, grounded in specific instances from the teachers' classes, provided not only ideas for instructional strategies, but also new diagnostic possibilities, an exchange of resources to support the intellectual work of teaching.

In this respect, in their ongoing inquiry into students' understanding and participation, teachers have much in common with education researchers, specifically those who conduct research on learning. They study essentially the same phenomena, that is student learning, although in different ways, and it is reasonable to expect that teachers and researchers could support each other in their efforts. The central purpose of this project was to explore how that may happen, particularly how perspectives from education research may contribute to teacher inquiry. I will discuss this further in the section below, "A Role for Education Research."

Before that, however, I will present another example of a snippet conversation. This will serve further to substantiate the view I am promoting of teaching as inquiry and of teacher expertise as involving intellectual resources for engaging in that inquiry. The main purpose of the section, however, is to reflect on the language by which the teachers articulated their interpretations: The teachers often experienced and expressed what they perceived in students as ideas for how to proceed in instruction.

INTERPRETING LAB REPORTS ON SIMPLE CIRCUITS: DESCRIBING PERCEPTIONS IN A LANGUAGE OF ACTION

Our meeting on December 12, 1996 opened with a snippet from Lis, a videotape produced by two of her college prep students as part of an optional project. They had performed two experiments in projectile motion. First, they fired a BB-gun across a field at a target, measuring the distance the BB fell in its trajectory below the horizontal, and showing that this distance, ten inches, was consistent with a calculation from kinematics equations they had learned in class. Their second experiment was to throw two pumpkins from a cliff, launching

them horizontally at different speeds. They measured the times the pumpkins took to fall and the distances they fell outward from the cliff, again to compare with the theoretical predictions.

There was much to discuss about this tape, including the students' investment in their work, the validity of their reasoning and measurements, the value of their "seeing" the BB fall ten inches in its trajectory, as well as the students' campy humor. The conversation digressed often from the details of the videotape to talk in general about the motivational and conceptual value of real-world and open-ended projects, together with strategies for assigning and assessing them.

Here I will focus on the second snippet, which Hilda assembled by use of student reports and her observations of their much more traditional laboratory work. In one lab, the students systematically varied the voltage and resistance in a simple series circuit by changing the resistor or the number of batteries. They measured the voltage and current using three different resistors for each of at least five values of voltage, and they plotted their results on graphs to confirm Ohm's Law.⁷

Most but not all of the students' lab reports were in line with what Hilda had intended. For her snippet, Hilda collected some of the aberrant responses to questions in the results section, including "What happens to the current when the voltage is increased (R constant)?" and "What happens to current when the resistance is increased (V constant)?" The following is quoted from Hilda's snippet.

Despite a discussion of cause/effect, there were still those who answered:

"The current would decrease, as would the voltage, as the resistance gets greater, it allows less electrons to pass through the circuit at a given time." Then, in her conclusion, she said: "We could also see that when the resistance stays the same and the current increases, the voltage would increase in proportion to it. This could be proven by $R=V/I$."

Even though they answered the questions correctly, in the conclusion where they are required to sum up, there were those who said:

"We discovered that as current decreases the voltage decreases and the resistance increases."

"Because the R must remain constant with each circuit set up, if the current is decreased, then the volts must be increased to compensate. This satisfies the equation and makes sense because in order to compensate for a lower current due to a higher resistance, the volts must be higher in order to push the electrons through."

“When the current flowing increases, the circuit voltage increases.”

“As the current increases, the potential difference increases.”

Included in “sources of error” were:

“The batteries: as we used them they lost energy.”

At the end of the snippet, Hilda added a comment about work by one group on a previous experiment that had impressed her favorably:

I'd like to mention a really interesting way that one student saved her group's experiment that was measuring with a tangent galvanometer the dependence of its magnetic field on the strength of the current. In this PSSC experiment, a light bulb is used in the circuit to limit the current and to show that there is current. About halfway through the process of winding on coils one at a time the light bulb blew! After changing the bulb they saw that the compass needle deflection increased by a much larger amount than expected for a single coil increment. One of the girls recognized that it must be a different bulb letting more current flow in the circuit—this was before doing the Ohm's Law experiment! She was able to select a bulb like the one that burned out, and they were back to similar increments.

Our Conversation

John opened our conversation about Hilda's snippet with an interpretation of the difficulty some of the students had on the Ohm's Law lab and his suggestion of a way to address it.

John: I look at this, and my thought is, one of the toughest concepts that over the years I have had to try to teach is what electric potential or voltage is in the first place. Students come into class, and they've talked about volts . . . all their lives, [but] essentially nobody knows what it is. And about five years ago somewhere I got my hands on a piece of shareware called “Circuit Vision.” I can bring in copies. It runs on a Macintosh.

This software, John described, allows the user to build a virtual circuit, made up of batteries, resistors, and wires. The program then enacts a mechanical analogy of that circuit, showing current as the motion of little balls. Little escalators carry the balls from lower to higher levels, analogous to batteries lifting charge to

greater voltage, and the balls push paddle wheels as they fall back down, analogous to charge expending energy as it moves through a resistor to a lower voltage. In this way, the program visually presents an analogy between electric potential (or voltage), meaning the *electric potential* energy per unit of charge, and *height*, which can be understood as the gravitational potential energy per unit of mass.

John: And I think, as a result of that, students get a better concept sooner of just what voltage is. And some of the questions, I mean, this one question that somebody made in the middle [reading from Hilda's snippet]: "Because R must be constant with each circuit setup, if the current is decreased then the volts must be increased to compensate," as if somehow voltage and power are different measures of the same thing—one goes up, the other one's gotta go down.

Hilda: [Agrees.]

John: Others are just kind of looking at it as a mathematical equation. In some cases they're getting it right, getting the mathematical equation right, but I still get the feeling they have no idea what they're talking about.

Hilda: No, that's the thing. That's right. In other words, the inverse proportion is there and the mathematical equation, but it's not there in terms of the concepts.

Hilda elaborated, in a tone of amused exasperation, her perception of how the students were using the equation:

Hilda: [They were] using the equation as though it were pure numbers and not [as though it was] a measurement of anything that had significance. So, when I talked about it, I talked about it as a cause and effect idea. Or, sometimes I'd say to them, "You know, we put the cart before the horse. You've got things not in sequence. What's controlling what? We often talk about an independent variable, [and] a dependent variable. What's the control here?"

That is, Hilda was noting, the students had manipulated the voltage by changing the number of batteries they connected in series. Several students nevertheless described their observations as though the change in voltage resulted from the change in current ("as current decreases the voltage decreases and the resistance increases"). In this way, Hilda was saying, they were not making a meaningful connection between the equation ($V = IR$) and their measurements in the lab.

We also spent some time talking about the group of students who had discovered they were using the wrong bulb. Hilda recounted a similarly impressive episode in which a group of students, working on the Ohm's Law lab, had found that their measurements did not correspond to the markings on a resistor, ultimately to decide it was mismarked. Hilda described what impressed her about these cases:

Hilda: I thought they did a really good thinking job there. Where they weren't going to just write down this number and say, "I've got 200% error" or something like that. [They] came over to say, "You know, we really think that this one's [mismarked]."

David: So that's another example sort of analogous to this one [in the snippet].

Hilda: Yeah, yeah, where they are showing greater sense. . . . that something that's different isn't, "uh-oh, we've got some errors in our experiment," but they looked for what could make this happen so that they could talk about it, that's what actually they did in their report. [In contrast to] one girl [who] just reported 200% error and didn't bat an eyelid. . . .

David: So . . . they found some discrepancy and they were committed enough to the ideas to deal with it.

Hilda: *Right.* Exactly. I can't even, sometimes they go through a whole experiment and they don't even notice if they've got some really anomalous data that just doesn't fit.

For Hilda, this problem went beyond this particular experiment. She proceeded to describe another example, in which students had somehow misread a scale to find that it took more force to pull a cart up a shallow than a steep incline.

Hilda: But they don't notice [the mistake] until you look at their numbers and ask them, "What went wrong here?" . . . They're doing exactly what they were told to do and they don't really see, is it good data or is it not good data.

This reminded John of students' failing to catch absurd answers on their calculators, specifically in finding trigonometric functions of angles measured in radians when the calculators are set to measure angles in degrees. Robert saw this as a general liability of their inordinate faith in calculators, which can lead them to accept results such as that "a person's height [is] 43.5 meters." John noted that

he “had that problem before calculators,” and everyone agreed calculators were not the root cause.

Our conversation turned to this topic in general, of students who do not notice absurdities in measurements or in calculations. Referring back to Hilda’s examples of those who did notice and resolve inconsistent results, I asked why other students do not do this and whether it is something they could be taught.

Hilda: I had a discussion about that one time and [the students said] they figured I was doing something to trick them. That if I’m giving them problems on a test, the numbers don’t have to be real numbers and so I could make it come out like a person can be 43.5 meters tall. I got into this mode then, of telling them.... “This is a real problem. There’s no tricks. The numbers should be the order of magnitude of what you would expect.”

Ed referred back to Lis’s snippet as an example of an instructional approach that might help.

Ed: One answer to your question, to the teachable-ness of this, is to give them a BB-gun, take them out in the field and have them make a video, and see whether the ten inches is [real]. They even did the conversion to meters—that was very impressive. I wonder, is that a way to make them [think of the results as meaningful]?

Ed’s comment about the students’ having converted to meters prompted an exchange about the prevalence of unfamiliar units in introductory physics. Lis remarked that “we didn’t grow up with kilograms. And I think that they don’t really know what [it means].” John agreed, “Except for seconds, pretty much everything we deal with in physics is not real to too many students.” The rest of the conversation stayed with the general topic of the connection to “reality,” considering the influence of students’ experiences in mathematics classes and whether it is helpful or harmful for them to practice methods of calculation they do not yet understand.

Teacher Perceptions

Again, our conversation about the snippet reflected a variety of interpretations of the students’ understanding and participation. To review, these included perceptions of the students’

- ▶ **difficulty with the concept of electric potential (voltage).** John opened the conversation with this thought and proceeded to describe a piece of software he has found helpful. Given a simple electrical circuit, this program depicts a mechanical analogy to help students visualize electric potential as analogous to height.
- ▶ **treating the mathematics as disconnected from the concepts...** Some students, John noted, were struggling with the conceptual relationship, whereas others were just “looking at it as a mathematical equation,” without regard to its meaning.
- ▶ **...as well as from the procedure and measurements in lab.** Hilda also felt that the students were “using the equation as though it were pure numbers,” rather than as though it involved quantities with physical significance. In particular, Hilda was referring to the lack of correspondence between the students’ explanations and the procedure they had followed in the lab.
- ▶ **trying to make sense of discrepant data.** Hilda wrote about one case in her snippet, of students who discovered that they had inadvertently used a different type of bulb, and she told us about another in our conversation of students who determined that a resistor was mismarked. Hilda was impressed that “they looked for what could make this happen so that they could talk about it,” in contrast to others who simply attributed discrepancies to “experimental error” without looking for any specific cause.
- ▶ **ignoring their common sense in thinking about physics.** Toward the end of this conversation we digressed from Hilda’s snippet to talk about a general perception of students, that many do not treat physics as connected to reality. Hilda told of her students’ saying they expect her to trick them and of her developing the habit of reassuring them that there are no tricks. Ed spoke of Lis’s snippet as a means of teaching students to treat physics as real.

It may seem surprising that a group of teachers could find so much to discuss in these snippets, which to the untrained eye are fairly sparse excerpts and observations. The first point in this chapter, however, is that these are not untrained eyes. Working every day with students, teachers become adept at interpreting what they see and hear. Like physicians for whom a handful of symptoms in a patient may indicate a variety of possible conditions and courses of treatment, these teachers have developed a wealth of knowledge and experience, intellectual resources for thinking about students.

It is unusual, however, to understand teaching in this way, including among teachers. Even in these conversations, the teachers often seemed more inclined to talk about instructional materials and techniques than about interpretations of student statements and behavior. If inquiry into student knowledge and reasoning is at the core of teaching and teachers' expertise, as I am suggesting, then why would teachers seem reluctant to have conversations about it? This section concerns the second point of the chapter, that teachers often talk about their interpretations by talking about instructional materials and techniques.

A LANGUAGE OF ACTION

I had tried at the outset of this project to impose a ground rule. In conversations about snippets, we should restrict ourselves to comments that concern students' statements and behavior rather than what the teacher did or should have done. I had two reasons for imposing this rule. The first was to promote a focus on perceptions of students, rather than on the means for addressing them. The second was to encourage an atmosphere of respect for the teacher presenting the snippet. Too often, I had experienced conversations about teaching degenerate into uncomfortable and unproductive criticism of the teacher's actions.

My rule proved difficult to enforce, however, and, in the end, counterproductive. A key example from the first year was John's "turn on the room lights" strategy (which Bruce recalled during our conversation about Robert's snippet). Discussing another teacher's snippet, John had offered this:

John: [I say] things like, "You know, what if the room lights come on and you see the ball already going down the alley. You know somebody pushed it, but you have no idea who pushed it. All you can say is, well, here it is right now. Now tell me what forces act on it." And sometimes they get it when I talk about room lights coming on. You know, I've had some trouble getting them to forget about earlier things.

What we came to recognize was that, while most of John's comment was explicitly to suggest a teaching strategy, it was also implicitly to express his interpretation of what was happening in the snippet, that the students had not distinguished a force *acting* on an object from a force *having acted* on the object a moment ago. Moreover, John's description of his strategy was helpful in communicating his interpretation to the rest of us, including the snippet's author, who as a result came to understand the students' thinking differently: "Yeah...I think

maybe [that was the idea] these kids really had. Not so much that they thought it was pushing now. But more that it was pushed then.”

This moment led us to the realization that a comment about teaching strategy may also serve to convey interpretation, and we were then able to recognize that this was happening fairly often. In other words, the teachers were often communicating “what to see” in the students’ understanding and participation by suggesting ideas of “what to do” to help them. Their suggestions for methods and materials thus often had a dual purpose: explicitly to suggest instructional action, and implicitly to suggest a diagnosis of the situation.

For this reason, to rule out comments about teaching would be to rule out a principal mode by which the teachers discuss their interpretations. From the teachers’ perspective, adherence to my rule made our conversations inauthentic, disconnected from their knowledge and experience, and we decided to abandon it. Perhaps it had served a purpose at the beginning, promoting a level of sensitivity and mutual respect in our conversations, but we came to see it as an impediment.

Our conversation about Hilda’s snippet contained several examples of comments explicitly concerning ideas for instruction that served as well the role of expressing an interpretation.

The first example was again John’s, who identified in Hilda’s snippet a pattern he had seen before, of students’ difficulty with the concept of voltage: “essentially nobody knows what it is.” He went on to describe what he has found to be an effective means of addressing this difficulty, a computer program that displays mechanical analogies of electric circuits, with voltage analogous to height. By describing the computer program, John was not only suggesting it as an effective approach; he was also specifying what he saw as the problem, clarifying considerably what he meant by “nobody knows what it is.” In particular, John saw the students as lacking what researchers might call a “mental model.”⁸ He went on to note that some students “were getting the mathematical equation right, but . . . they have no idea what they’re talking about,” and Hilda agreed: “That’s the thing. . . the inverse proportion is there and the mathematical equation, but it’s not there in terms of the concepts.” As the conversation continued, however, it became apparent that Hilda and John differed in interpretation of what was the problem, or, at least, they were fixing on different aspects of it.

When Hilda elaborated on her interpretation, she explained that the students had been “using the equation as though it were pure numbers and not [as though it was] a measurement of anything that had significance.” She explained how she

had tried to address this in class, and this clarified what she meant by “a measurement . . . that had significance:”

Hilda: I'd say to them . . . “You've got things not in sequence. What's controlling what? We often talk about an independent variable, [and] a dependent variable. What's the control here?”

Thus Hilda was primarily concerned that the students did not connect the mathematics with their experience in the lab: They had manipulated voltage by changing the number of batteries, but in their reports they described the voltage changing as a result of changes in the current or resistance. This was a different perception from John's that the students lacked a conceptual understanding of voltage. For example, with different equipment the students could have manipulated current as the independent variable. In that case, a student could appropriately have written, “When the current flowing increases, the circuit voltage increased,” and Hilda's concern would not apply. John's still could, however, because that statement, an empirical summary of the experimental findings, does not indicate what the student understands about the concepts.

Hilda agreed with John that the students did not understand the concepts, but she attributed this to a more general problem that they did not expect ideas in physics to make sense. She was saying, in effect, that the students were all capable of keeping track of what quantity they were measuring. That their explanations did not reflect what they had seen suggested they did not expect the relationship they were studying, Ohm's Law, to have tangible meaning. John's interpretation, in contrast, was specific to this content: The students did not understand the concept of voltage. On this interpretation, these students may not have been able to keep track of what they were doing in the lab, because they needed a mental model for reference. To understand that the voltage in the circuit is determined by the number of batteries, for example, requires an understanding of voltage.

It was not our purpose in discussing this snippet, nor is it my purpose here, to decide which of these interpretations is correct. Either could apply for particular students in particular situations. As a matter of principle it is probably best left to the teacher, in this case Hilda, to make that judgment, because, in the end, she has the most information about her students. My purpose here is to suggest that Hilda and John interpreted the students' understanding and participation in different ways, and that we learned this primarily from what they said about instructional action—John describing what he would do and Hilda recounting what she did.

Later in the conversation, I asked why some students do not try to reconcile inconsistencies, as did Hilda's students who had worked hard to understand anomalous data, and whether this was something they could be taught to do. Ed suggested that one answer might be to give students more experiences of the sort we had seen in Lis's snippet, in which a group of students had conducted their own experiments in projectile motion, shooting a BB-gun across a field and tossing pumpkins from a cliff.

Ed's suggestion was one more example of a perception described in a terms of instructional action. He was, in effect, offering another interpretation of why students may not expect physics to make sense. Hilda had told of her students' suspicion that she might do "something to trick them," and how she had responded by saying she would not, an interpretation of the problem as arising out of a specific, articulable belief. Ed was considering the possibility that, for some students, the disconnection between physics and everyday experience lies more deeply, in a more general and less articulate sense of physics as taking place in a different domain of experience from their own, an interpretation similar to perspectives of knowledge and reasoning as "situated."⁹ For such students, addressing the problem would not be as simple as telling them common sense applies; it would involve constructing with them a context for physics that directly engages their everyday experience.

In this way, Ed was using the idea of assigning real-world projects to help him express and refine his ideas for why students may not expect physics to make sense. In fact, much of our conversation about Lis's snippet earlier could be seen in this way: Lis had presented us with an example of an assignment designed to address aspects of students' understanding and participation not addressed by more conventional assignments, and our conversation about it drew our attention to those aspects. By referring to Lis's snippet, Ed brought those considerations to bear on the issue we were discussing at this moment, of students not treating physics as meaningful.

Teachers spend much of their time and thought in gathering and interpreting information, trying to gain insight into their students' understanding and participation. In this way, they have much in common with those engaged in formal research on learning. Still, there are important differences. Researchers intend their inquiry to produce explicit, articulate perspectives and claims, supported with arguments and evidence that can withstand peer-review. Teachers inquire toward action, in the contexts of their classes and presumably to the benefit of their students, with little time or opportunity for explicit reflection and awareness, let alone for public articulation. In short, researchers

publish, whereas teachers *act*, and this difference is reflected in the ways in which they experience and express their respective insights into learning and instruction.

In the following section I present a third and final example from our conversations, illustrating a role for education research. I suggest that the interaction between the practice of teaching and the practice of education research should be understood principally on this common ground of inquiry into student understanding and participation.

INTERPRETING A TEXT ON PLANETARY MOTION: A ROLE FOR EDUCATION RESEARCH

One of the snippets we discussed on December 16, 1996 concerned the students' responses to two questions from a test on planetary motion and gravity, which Bruce had given to his twelfth-grade college-prep students. As part of his snippet, Bruce explained that the class had seen and discussed the PSSC film *Frames of References*. Much of their discussion was of what reasons there were for believing the earth goes around the sun, and what reasons there had been for earlier beliefs that the sun goes around the earth. Bruce noted that they had explicitly addressed whether the apparent motion of the sun across the sky was a reason for believing the earth moves: Airplanes and clouds also move across the sky, but that is obviously not reason to believe the earth is moving.

Bruce: Nevertheless, to the true-false question: "The rising and setting of the sun proves that the earth spins on its axis," eighteen of twenty-five students answered "true." Since we explain this observation today by saying the earth is turning, I can understand such a response from those who forgot the film and our discussion.

However, halfway down the page was this question: "State two reasons why earth-centered models of planetary motion were favored for so long over sun-centered models." Ten of the eighteen who had answered the previously-discussed question "true" nevertheless used the apparent motion of celestial objects as a reason for this too. Typical answers included:

Student 1: "...when they saw the sun rising at the east + setting at the west, they concluded that the sun went around the earth."

Student 2: “People believed that the sun traveled around the earth because the sun rose and set every day.”

Student 3: “It seemed that the sun rotated around the earth because of the change in day and night.”

What surprised Bruce was the number of students who could, on the same test, answer both that people had once thought the sun’s apparent motion was actual, and that the sun’s apparent motion across the sky “proves” the earth rotates.

And, although the top two scorers on this test answered these correctly, there was no pattern to who got these right or wrong. This seems to me a perfect (in fact, extreme) example of the “pieces” approach to learning physics—that ideas don’t have to fit together or even make logical sense!

Our Conversation

In our conversation, Bruce explained that he sees this behavior often.

Bruce: I see this kind of disconnect a lot. I’m sure we all do. But I was surprised there were so many of them, this time. Particularly when they had seen the film and we had discussed things over. And these two questions were on the same page, about half a sheet apart.

John suggested that some students might have read the question as the rising and the setting of the sun *reflects the fact* that [the earth spins on its axis], rather than *proves*. Bruce agreed that was a good possibility—in fact, one student had told him she answered “true” to the first question “because the rising and setting can be explained by the earth spinning”—but he felt this was consistent with his interpretation: Given the emphasis on this point in the class discussion, it was odd that a student would misinterpret the question in this way. That a student would treat “proves” as equivalent to “can be explained by” suggests the student was not paying attention to the logical connections among ideas.

In a similar vein, Lis noted that both parts of the statement in the first, true/false item are “true”: The sun does rise and set, and the earth does spin on its axis. Seeing two true statements joined in a sentence, the students may have been distracted from the logic of their relationship, especially under the duress of a test. Hilda and John talked about these as general liabilities of true/false and multiple-choice questions, that they are open to such misreadings, that they invite

test-taking strategies, such as trying to second-guess the test author's intentions, and that it is difficult to know why students answer as they do, even when their answers are correct.

Still, returning to the snippet, Hilda affirmed Bruce's interpretation, in part because of her own similar experience.

Hilda: They don't see that they're answering this one, which contradicts that one. Because I very often have that [happen]. You know, they're doing the exact opposite for those two questions, and they're not seeing the connection when we go over it in class.

Lis's first reaction to the snippet, however, was surprise at a difference from what she had seen in her students. Early in the conversation she remarked that her students seemed to have a head start on this topic, having considered in previous classes the transition from an earth-centered to a sun-centered worldview "at a philosophical level."

Lis: They do a lot in humanities that follows right along with [these ideas in] mechanics. . . . They all do. It's amazing. I mean, they would be using the words "geocentric" [and] "heliocentric." They would be quoting Aristotle. . . .

Lis emphasized that she was not referring to a technical familiarity, the ability to solve physics problems; she was referring to a familiarity with these larger systems of thought and the general shift in popular belief.

Later in the conversation, Lis observed that the students in the snippet had all approached the test question, which asked why people had favored earth-centered models of planetary motion, as a question about physical objects rather than about people and how they form beliefs. Their answers referred to the sun's apparent motion in the sky and the earth's rotation, rather than, for example, to the influence of the Church and popular religious convictions.

As in the previous two examples, the snippet and our conversation about it raised a range of interpretations of the data, in this case student responses to two questions on a test. Research on learning may have contributed to that range.

A Role for Education Research

By and large, the education community tends to think of the connection between research and teaching in terms of instructional methods and materials: Research on learning should have implications for what teachers should do in class,

whether to form cooperative groups, adopt microcomputer-based materials, or assess through student portfolios. Research, in short, should establish and prescribe effective methods.

We set out in this project to develop a different understanding of the relationship between teaching and research on learning, at the level of interpretation rather than method. Instead of asking how researchers' findings should inform teachers' techniques, we have been asking how researchers' interpretations may inform teachers' interpretations. To that end, we read articles from the research literature, considered the perspectives they presented, and asked what insights they could provide into the snippets we were discussing. Instead of methods or general principles, we were looking for insights into particular moments of learning and instruction.

I have been especially interested in the possible contributions of my own research on student learning. During the first year of the project, I asked the group to read two of my articles on students' beliefs about knowledge and learning, or student "epistemologies." We read one of my articles in May, 1995 (Hammer, 1995) and another in November, 1995 (Hammer, 1994). Bruce was referring to that work when he called the exam results an "example of the 'pieces' approach to learning physics": "Pieces" was the term I had used to describe the belief that physics knowledge is a collection of independent, disconnected pieces of information, as opposed to a connected, coherent system of ideas.

The important point here is that Bruce's use of the perspective in discussing his snippet reflects an influence at the level of interpretation: He saw his students as not attending to the connections among ideas. In fact, Bruce described this sort of contribution to his thinking on several occasions. In one other case, for example, he was discussing a snippet he had written to recount how three of his better students, working on a problem about light reflection, had concluded that one's image in an ordinary mirror is upside-down which is contrary to everyday experience.

Bruce: He apparently never made the connection even though we'd talked about it, that this is like when you look at yourself in a mirror on the wall. Or else how could he possibly put it upside down? In that sense it seemed to be an example of your [David's] kind of disconnection between reality and physics class.... Prior to reading your article, a couple of years ago I probably wouldn't have thought of it any other way except, well they just confused [ordinary mirrors and curved mirrors] and didn't think what they were doing.

In other words, the perspective gave Bruce a new diagnostic option for understanding his students, one he has applied and found useful in certain circumstances. This is a more modest but, I contend, more appropriate role for research on learning than what is generally assumed in the education community, that research should contribute at the level of instructional method.

If this is the role I as a researcher expect my work to play, then conversations such as these are essential, both in developing the ideas themselves and in understanding how they may or may not contribute to teacher perception and judgment. To be sure, our conversations led me to reconsider both the perspective and how I have presented it. I will not pursue that topic here except as follows, specifically regarding the language of action I discussed in the previous section.

In designing this project, I had assumed a clear distinction between diagnosis and action. That assumption helped shape my thinking about the role of education research. Consistent with the philosophy behind “Cognitively Guided Instruction” (Carpenter, Fennema, & Franke, 1996), I consider teachers to be in a much better position than I to derive methodological implications for their practices. For that reason I had been careful to avoid prescribing methods in writing about student epistemologies.

I was taken aback, therefore, by Bruce’s describing what he found useful about my articles: It was not, he explained, the presentation of the theoretical framework but the ideas they contained for what to do in class, which he drew primarily from the classroom episode and discussion of instructional strategy (in Hammer, 1995). On the other hand, it was clear from his comments that he used the perspective as a diagnostic option for understanding his students. That Bruce considered the articles most useful with respect to the ideas they provided for instruction, I contend, is another example of the melding of interpretation and method in the language of action I have described. As we discovered in the failure of the ground rule I tried to impose on our conversations, for teachers diagnoses of student strengths and needs are tightly interwoven with strategies for addressing them.

I maintain that offering insights into student understanding and participation is a more appropriate role for education research than prescribing methods, but it is not inappropriate for education research to *suggest* methods. From our experience in this project, suggestions of method are an important means of communicating those insights.

This project was designed to study how perspectives from research may contribute to teacher perceptions, but there have been signs throughout our conversations of what teacher perceptions may have to offer education research. One

example was Lis's observation that the students' had used technical rather than social language to answer the question on the test. This could be the kernel of a doctoral dissertation: What might affect students' choice of a mode of reasoning or discourse? Under what circumstances would they have approached the question as an issue, for example, of how people are swayed by popular opinion? More to the point, Lis's insights in this regard should be of interest to researchers investigating discourse in science teaching (e.g. Lemke, 1990; Roth & Lucas, 1997).

In sum, teacher inquiry overlaps substantially with research on learning. Both involve observing students and examining what they produce, so it is not surprising that they arrive at similar ideas. But there are important differences between the practices of teaching and research: Researchers publish whereas teachers act.¹⁰ Having an insight into student understanding and participation, a researcher asks, in essence, "What can I say about this?" whereas a teacher asks "What can I do about this?"

The differences in practices are reflected in differences of language, as we have found in this project, and these present a challenge to substantive exchange between teacher inquiry and research on learning. At the same time, the differences represent complementary strengths: Researchers can and must focus on developing narrow, articulate views; teachers can and must be more broadly aware and responsive. We have explored the role perspectives from research may play in supporting teacher inquiry, but the benefit should certainly be mutual.¹¹

TEACHER INQUIRY AND STUDENT INQUIRY

To return in closing this chapter to the central theme of this book, nowhere is effective exchange of insights among teachers and researchers more important than with respect to student inquiry. There are many calls in state frameworks and national standards for a greater emphasis on student inquiry in science education. As a general nicety, student inquiry seems a simple, desirable goal. In specific contexts of instruction, however, it is not a simple matter at all. No one understands clearly how to discern and assess it, or how to coordinate it with the more traditional but still important agenda of covering the content. This, of course, is not for lack of trying, but attempts by philosophers of science to define what is the scientific method (e.g. Popper, 1992/1968) or by educators to specify "process" skills as appropriate educational objectives (starting with Gagné, 1965) are widely considered unsuccessful. If it is possible to capture the essence of scientific reasoning—and some agree with Feyerabend (1988) that it is not—it has not been done.

The physical sciences have achieved stable, precise, and principled systems of knowledge. Working within these systems there is much that is, at least in practice, objectively true: There are clear, reliable, and reproducible methods, for example, for determining atomic masses or for manufacturing light bulbs. Education research has not achieved this quality of understanding; for good or ill, it is not possible to provide teachers clear, reliable, and reproducible methods for assessment and instruction. Interpreting student understanding and participation remains highly subjective, and this subjective judgment inevitably falls to the teacher, in specific moments of instruction like those recounted in the snippets here.

Moreover, this discrepancy between the quality of knowledge *within* science and the quality of knowledge *about* science and science education has particular significance for teachers trying to coordinate objectives of student inquiry and traditional content. It is, in general, relatively straightforward for a physics teacher to recognize when a student's answer to a question is correct or incorrect, judging it against the established body of knowledge. It is not difficult, for example, to see that the student in Robert's snippet was incorrect, from a Newtonian standpoint, when she said that "the force of gravity is getting bigger." It is not at all straightforward, however, to assess her *understanding*, to determine whether her comment reflects a misconception, which will prevent her from learning Newton's Laws if it is not eliminated, or a valid insight that will help her if she is encouraged to develop it. Nor is it straightforward to assess her reasoning as inquiry, for example to measure the value for her of having contributed an original idea or to weigh that value against the fact that it was incorrect.

Robert often expressed his concern that students learn to engage in scientific reasoning, rather than simply cover the content with a superficial understanding of the ideas. To pursue his objectives, however, to have conversations such as that he presented in his snippet, Robert must compromise the traditional content of the course. He must be able not only to reconcile this for himself, but also to justify it to administrators, parents, and students, all of whom will be aware that his class has not covered as much of the textbook as other classes. What should he tell them? How can he make what they have gained as tangible as what they have lost?

Similar tensions arise in other snippets. To pursue many activities of the sort Lis assigned, which led to the students' videotaped experiments in her snippet, would similarly diminish the traditional content. How should she consider and describe the relative value of those activities, as compared to other more familiar activities, as she plans the distribution of time over her year?

Hilda saw differences among her students, not only in the correctness of their reasoning, but also in the quality of their reasoning. A number of her students had followed the instructions of the lab and arrived at mathematically correct conclusions, but their thinking troubled her. It contrasted with the work of other students who had identified sources of discrepancies in their measurements. Precisely how should she interpret the differences between these students—was it interest, intellectual ability, confidence, all of these?—and what is largely an equivalent question in the practice of teaching, how might she design instruction to promote the more impressive reasoning? And, again, how should she weigh the value of that agenda against the value of covering more material?

Bruce saw, in his students' responses to two test items, an indication that they were approaching physics as a collection of incoherent facts. How should he value that perception against his perceptions of the correctness of the individual responses? Should students who are less consistent in their responses to questions on an exam, but get a greater percentage correct, receive a higher or lower score than students whose answers are more consistent but have a smaller percentage correct? This may be seen as a conflict between valuing "inquiry" (the internal coherence of a student's reasoning) and valuing traditional content (the correctness of a student's individual answers with respect to the intended body of knowledge).

If we are to achieve student inquiry-based science instruction, we must do much more to appreciate and address the intellectual demands that places on teachers. This will require developing conversations among and between teachers and researchers, much more than is currently occurring, and these conversations should begin from specific, authentic episodes of learning and instruction.

ENDNOTES

1. The project described in this chapter was funded by a joint grant from the John D. and Catherine T. MacArthur Foundation and the Spencer Foundation under the Professional Development Research and Documentation Program and by a grant from the DeWitt Wallace-Reader's Digest Fund to the Center for the Development of Teaching at the Education Development Center in Newton, MA. This chapter, however, is solely the responsibility of the author and does not necessarily reflect the views of any of these organizations. I am most grateful to Lis,

Hilda, Ed, Bruce, John, and Robert for participating in this project, for all their help and ideas in designing and redesigning it, for the windows they provided into their practices, as well as for their critical readings of several drafts of this paper. Thanks also to Denise Ciotti, Kass Hogan, June Mark, Jim Minstrell, Peggy Mueller, Barbara Scott Nelson, Mark Rigdon, Ann Rosebery, Annette Sassi, Deborah Schifter, and Emily van Zee for helpful comments, suggestions, and questions.

2. *Exploring the Place of Exemplary Science*, edited by Ann Haley-Oliphant, includes several chapters that discuss teaching as inquiry into student understanding and participation. See especially the chapters by Julia Riley, "Improvisational Teaching"; Robert Yinger and Martha Hendricks-Lee, "Improvising Learning Conversations"; Betty Wright, "How Do I Read my Students"; and Kenneth Tobin, "Learning From the Stories of Science Teachers." Other writings include Duschl and Gitomer (1997) on assessment conversations as tools for teacher inquiry into student understanding, and Hammer (1997) in which I present an account of my inquiry as the teacher in a high school physics class.
3. See Schön (1983) for an account of the nature of expertise in reflective practitioners.
4. All are public secondary schools in Massachusetts with the exception of Dana Hall which is a private school for girls. The teachers were recruited through letters and phone calls and were compensated as consultants. The project began in March 1995 under the auspices of the Teachers' Research Network of the Center for the Development of Teaching at the Education Development Center in Newton, MA. Initial funding came from a grant from the DeWitt Wallace-Reader's Digest Fund. When that ended in June 1996, the MacArthur/Spencer Professional Development Research and Documentation Program provided support for two more years.
5. All of the schools have recognizable distinctions among levels of physics classes. At the top level are the Advanced Placement classes, which are almost always the second year of physics instruction. Among the first-year courses, there are the honors courses, which may be calculus-based; algebra-based college prep courses, typically with two or three sections; and, at some schools, a conceptual level with minimal mathematics.

6. Ellipses indicate where I have omitted portions of the transcript. Square brackets indicate words I have substituted or added to the transcript for clarity.
7. Ohm's Law is a relationship among the electric potential or voltage (V), the current (I), and a resistance (R), usually written " $V = IR$." It states, in essence, that the voltage across a resistor and the current through the resistor are proportional: The higher the resistance, the greater the ratio of voltage to current.
8. Gentner and Gentner (1983) discussed students' different mental models of electric current and voltage.
9. Brown, Collins, and Duguid (1989) is probably the most well-known reference.
10. It is for this reason that I have mostly referred to teachers' interpretations as perceptions and researchers' as perspectives. This is not to imply that teachers do not have perspectives or that researchers are unperceptive; it is to connote different modes of inquiry, one more characteristic of teaching and one more characteristic of research. The practice of research requires that interpretations be made articulate in presentations, publications, and proposals, whereas the practice of teaching requires action, responding to students during class, choosing or designing materials and assignments. To act responsibly, teachers must perceive more than anyone could articulate; to be articulate, researchers must omit from their perspectives much of what they see.
11. For extended discussions of the value of teacher inquiry for education research, see Cochran-Smith and Lytle (1993) and Schifter (submitted).

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Inquiry in the Informal Learning Environment

Doris Ash and Christine Klein¹

In informal settings inquiry is a time-honored tradition as a way of learning. In this chapter we begin to explore ways to translate to more formal settings important underlying principles of inquiry in informal settings. Our important objective is to find what they have in common. In short, we look for areas of overlap and potential synergy. We hope to provide readers from each of the two settings with a new perspective on inquiry learning as it takes place in the other.

When asked how they first acquired a love for science, many scientists respond with poignant stories of playing with electronics or engines at museums, taking nature walks with a relative, watching spiders in the window, or making potions (or bombs) in the basement. All these contexts come under the general category of informal science learning environments. It can be argued that real learning occurs most easily in the informal learning environment and that human learning, over the centuries, has been characterized by an intellectual tradition of informal inquiry through observing, posing burning questions, hypothesizing, making predictions, doing research or experimenting to find the answers, interpreting and communicating.

Inquiry in informal learning settings, the basement, the lab, the museum, the zoo, has been defined as free-choice (Falk & Dierking, 1998), learner-driven, open-ended, unhurried, and personal. It is driven by attitudes of curiosity, what

Mikhail Csikszentmihalyi in 1990 identified as intrinsic motivation, and a willingness to be uncertain and to change directions as new evidence dictates. And inquiry is both a methodology and a vehicle for learning content. The processes, the content learned, and the effects are all critical components to inquiry learning. From the time of Socrates through the twentieth century work of John Dewey and Jerome Bruner, inquiry has been a habit of mind limited only by a person's capacity to learn and furthered by selection among the many ways of getting to an answer.

Here, in order to provide a template for translation to the classroom, we begin to examine deep underlying principles of inquiry learning in informal environments. We compare the general characteristics of learning in formal and informal environments, present vignettes from two existing programs that make use of inquiry learning, define common principles of the two settings, provide a template for implementing these principles in other contexts, and offer resources for educators to put them into practice.

FORMAL AND INFORMAL LEARNING ENVIRONMENTS

What do we mean by informal learning environments and how are they different from formal learning situations? The distinction often centers around the environment or context rather than the type of learning involved. Here we define formal environments as based in the classroom and informal environments as museums, science-technology centers, zoos, aquaria, botanical gardens, arboreta, nature centers, and similar settings.²

Centering on the inquiry learning involved rather than the setting, we start by looking closely at two successful programs, each concentrating on inquiry learning, each designed by informal learning centers. These are the Institute for Inquiry at The Exploratorium in San Francisco and the Compton-Drew Investigative Learning Center Middle School at the St. Louis Science Center.³ Between these two programs are some principles common to any inquiry learning setting, and as design features these can be built into many different learning environments.

Though we intend to move away from any stark contrast between informal and formal learning, the distinctions are helpful in planning the future. Table 1 compares the two for the characteristics of inquiry typical of each.⁴

TABLE 1. CHARACTERISTICS OF INFORMAL LEARNING EXPERIENCES

MORE LIKE	LESS LIKE
AFFECT/CHOICE	
fun, enjoyable, playful voluntary	repetitive mandatory
MEDIUM	
visually oriented real objects authentic task	oriented to text secondary sources tasks for others
SOCIAL CONTEXT	
individuals learning together directed by learning multi-generational experiences intrinsic motivation	instruction to a whole group directed by others one age group extrinsic motivation
INTERACTION	
highly interactive, learn by doing multi-dimensional interactions oriented to the process	didactic single dimensional oriented to topics
COGNITIVELY CHALLENGING	
multiple entry points—various ages	one or two grade levels
TIME	
short term self-paced open-ended single visits	long term other sets pace limited longitudinal

ASSESSMENT

self assessment based on feedback
serendipitous

formal assessment
multiple forms

STRUCTURE

non-structured
non-linear

highly structured
linear, sequential

One striking variable in Table 1 is the locus of control of the activity. In informal settings, the learner is usually in control of the activity and the learning. Another variable is the opportunity to understand what the learner takes away from the interaction. Informal settings are less likely to have strong assessment opportunities and long term observation, strengths of more formal settings.

Synergy Between Informal and Formal Learning Environments

Reviewing the characteristics of learning in the informal setting reveals a powerful and desirable constellation of traits that would be ideal in any classroom. Clearly there is a strong opportunity for reciprocity. Informal learning settings are self-directed, fun, playful, cooperative and highly interactive, traits that appeal to all settings. And indeed, some of the most successful classroom design experiments (Ash, 1995; Brown, 1992; Brown & Campione, 1996) include these elements and are modeled after good informal settings. Similarly some of the more powerful aspects of formal settings are becoming more attractive to informal educators: the prospect for long-term opportunity to understand the kinds of learning, types of reasoning, and change in knowledge that occurs at exhibits is attractive to designers in museums. These two areas, formal and informal, can inform each other, share expertise, and maximize synergy.

Museum schools are one example of a current trend in museum education toward a synergy of formal and informal learning.⁵ As classroom teachers and curriculum developers adopt more methods based in inquiry, the classroom takes on more characteristics of informal learning. As informal learning environments like science centers develop partnerships with schools, many programs acquire some of the strengths of formal learning. Here is a hypothetical example.

As students work on their projects, energy is brought to the classroom. The students are taking advantage of an opportunity to design an exhibition on space travel for the science museum. They began the project by generating their own questions about space travel and exhibition design, questions they would need to complete their projects. Now they are exploring those questions in small collaborative groups of their own choosing.

For an exhibit on the race to space, one group of students works at computers gathering additional information from the NASA web site on the history of the space program. One group works on an experiment that demonstrates the effects of zero gravity on various objects and considers how this experiment could be used as a hands-on exhibit based in inquiry. After questioning the one-sided results its members had found, another revisits its research notes on the environmental and economic costs and benefits of space tourism. As part of its background research on the role of science fiction in guiding space programs, still another reads a science fiction short story. A group works on calculations needed to bring a model of the solar system to scale on an exhibit. A sixth group of students is at the science center examining the existing exhibits and conducting evaluations of visitors.

As the extended class period draws to a close, the students gather together in jigsaw groups⁶ to share their expertise, teach one another, reflect on their progress, and compare findings. Plans for seeking additional resources and conducting additional experiments are made. All the students are eager to continue work when they return.

In this hypothetical classroom, students are intrinsically motivated and having fun. The exhibition at the science center provides the authentic task that drives their study of science, history, economics, literature, and mathematics. The broad idea for the inquiry is set by the science center and teachers, but students plan the details. Participation is mandatory, but students are eager to do the work. Students work in collaborative, self-directed groups. The teacher provides some structure and helps with project management, setting some of the pace to insure completion of the task on time. The final task acts as a formative assessment for teachers and students. Students receive feedback from their work and their peers as they move through their tasks, from the teacher as individual and group grades are given, and from science center staff as their designs go through the usual review process.

VIGNETTES OF INQUIRY AND RESEARCH FROM TWO PROGRAMS

That hypothetical example provides a picture of the synergy that can occur between formal and informal learning. A look in-depth at the two real examples that follow gives an even clearer image. In The Exploratorium's Institute for Inquiry, teachers, professional development specialists, and administrators develop strategies for bringing inquiry into the classroom and into national professional development efforts. In the museum school at the St. Louis Science Center, the strengths of formal and informal learning are central to the Schools for Thought (SFT) curriculum framework. As you read each vignette, please consider the principles common to both.

Two Inquiring Minds (The Exploratorium)

The Institute for Inquiry at The Exploratorium centers on inquiry learning for elementary school teachers, professional development specialists, and administrators, as a personal core inquiry experience and as basis for translation to the classroom and professional development. In this vignette, we describe the inquiry experience of two elementary school teachers in the Introductory Institute.

The core inquiry experience is designed to include a carefully crafted set of experiences that lead learners towards independently designed, long-term inquiry activities founded on their own questions.

At the beginning, everyone participates in a common set of experiences that give multiple entry points and diverse pathways towards deeper exploration. These experiences include light and color exhibits, paper chromatography, activities designed by artists, mixing color solutions, and many more. Working from their own questions, groups of participants define investigations and pursue them in self-selected small groups. These experiences are accompanied by group and individual "guided model building" initiated by the staff along with mini-lectures, demonstrations, and at appropriate times reference to related exhibitry. A few pivotal, guiding questions are repeatedly posed, for example, "What happens to the path of light as it travels toward your eye?" At the end of the investigations, groups teach one another what they have learned and together make sense of color, light, and pigment.

Light and Color: The Question.⁷ Terry and Connie's original experimental question was: "Can we recreate colors of marker pens by separating their pigments and then mix the primary pigments together to get the original colors?" This type of question had been asked in past Institutes and, in and of itself, could

not guarantee experimentation beyond the early exploration stage of inquiry. But throughout Terry and Connie's work, there were several clues that something important, beyond simple exploration, was occurring.

Taking Apart: Separating Pigments. Initially, Terry and Connie's focus, by use of a variety of color pens, was on using a diversity of solutions for chromatography color separations; they were careful with their technique; they inspected their results rigorously.

After several hours, Terry and Connie changed directions. "We did three solutions (with many different colors) then stopped." They felt that they were done with this part of their work and that doing chromatography with other solutions would give them no more useful, new, or discrepant information. They redirected their investigation, an act that told us that they were gathering information for a purpose, not just experimenting for the sake of data collection.

Putting Together: Mixing Color Pigments. The next part of their investigation complemented their earlier efforts. They wanted to mix color pigments to match the colors from the markers using the "primary" colors that they had seen separated out in their chromatography experiments. Their efforts to reproduce the original marking pen colors were exhaustive. For them to trust the symmetry of the problem, the process had to work in both directions: to be exactly reversible. They had to be able to take the color apart and then recreate it as well.

A difficult but illuminating instance was the reproduction of color for both light green and dark green pens. Terry and Connie had already determined that mixing cyan and yellow would produce green but no matter what the proportion of each, they could not match the dark green color. When they looked more closely at the results of their chromatography separation, in one sample they found something different. "We found out that to get dark green we needed to add a bit of magenta. It was so exciting...I guess you had to be there." "There" in this case included both the actual color separation and mixing and the excitement of charting new ground in understanding color pigment. By adding magenta to green, the two indicated they knew how to darken green pigment. They had tested complementary by making and breaking apart color pigment but had not understood why magenta darkened green. At this point they had answered their original question and might have felt that they could stop their investigation. Some nagging unanswered questions propelled them forward. Why did they need to add magenta to make dark green?

Making Sense of the Experience: "What Light Gets to Your Eye?" Throughout the color investigation we had advised people to think about a question that would help in making sense of the phenomena being investigated:

“What light gets to your eye?” At this juncture we suggested to Terry and Connie, whose experiments up to then had involved only color pigments, that they begin to explore color light and its interaction with pigments.

In looking back at Terry and Connie’s work it is evident that they had begun to use these ideas to anchor their thinking. They spent the bulk of their time working with pigment, while investigations with light by other groups surrounded them. Like the rest of the participants Terry and Connie took part in these investigations, by talking and observing as part of community sharing in formal and informal ways. Investigators from different groups sat side by side talking and sharing information so that Terry and Connie learned about phenomena they hadn’t investigated personally. It was the visit to The Exploratorium exhibits that proved to be the key to their understanding of the role of magenta in darkening green, and ultimately, to their creation of a model of light and pigment color in relation to absorption and reflection.

This model was articulated in their final presentation to the group. At that point Terry explained, “After we made the pen colors, we went to Color Removal.” Color Removal is an exhibit that uses a projector and prism to produce a bright spectrum. To show what filters do to the color spectrum, you place a color filter into the path of the light. It was in this interaction with light subtraction that the couple made the connection to the mystery of dark green. They saw that a magenta colored filter darkened only the green part of the light spectrum. Terry and Connie were able to use the new information from this exhibit, integrate it with their existing pigment work, and transfer their understanding to light and its relationship to color pigment.

In their final project presentation, according to Terry:

“We came up with the idea that:

<u>for pigment</u>	if you have all pigments / absorb all light / gives black
<u>for light</u>	if you have no light / no light can be reflected / gives black
<u>for pigment</u>	if you have no pigment / reflects all light / gives white
<u>for light</u>	if you have all light / all light can be reflected / gives white

It’s all about reflection and absorption.”

The analysis was correct. Adding all light colors together gives white light. Adding all pigments together gives black. This is best understood when the question is asked what light gets to your eye and what light has been absorbed or reflected by the pigment? Clearly Terry and Connie were using these ideas to tie together their investigations. The underlying complementary of light and pigment

in relation to the process of absorption and reflection in their model seemed a deeply compelling notion for them. They had moved from separating and mixing color pigment to an encompassing model of reflection and absorption in the interplay of light and pigment.

Lessons Learned. A central element to the power of inquiry learning is ownership of the overall process. We had already understood the importance of the question owned by the learner, as well as a personal pathway to inquiry, but along the way Terry and Connie learned some deep content and grew more confident in their abilities to do inquiry. They practiced using the processes of inquiry (observing, questioning, hypothesizing, predicting, investigating, interpreting, and communicating) to learn content. In this case we would not have guessed that extensive work with separation and mixing of pigments would be the foundation for understanding the interaction between pigment and color light. Terry and Connie created a unique path to creating meaning.

St. Louis Meets the Sea (Compton-Drew)

Compton-Drew Investigative Learning Center (ILC) Middle School at the St. Louis Science Center serves approximately 540 students from the St. Louis area in sixth, seventh, and eighth grades. In partnership with the St. Louis Science Center (SLSC), this magnet school is based on the concept of the museum school, in which museums and schools pool their strengths to form a unique educational experience (Klein, 1998).

The curriculum at Compton-Drew is developed by the teachers with support from SLSC staff and faculty from the University of Missouri - St. Louis. Curriculum is based on Schools for Thought, a curriculum framework and philosophy that utilizes the results of cognitive science research, that is, how we learn, think, and remember. This vignette tells the story of one Schools for Thought interdisciplinary unit conducted during the summer of 1997.

As students enter the classroom, they know by the circle of chairs in the room that they will be having a class discussion. This will be their opportunity to talk about what they know and think. Knowing the new unit deals with the sea, they anticipate the topic of the discussion. As they suspected, the teacher introduces the unit's theme, asks them what they already know about oceans and seas, and turns the discussion over to the students. This gives the teacher an opportunity to listen, to assess what the students know, and to identify incomplete understanding that will need to be addressed before or during the unit.

The following day the St. Louis Science Center's ILC Program Liaison introduces students to the unit's challenge.

The Science Center is showing *The Living Sea* at the OMNIMAX®. We like to make connections between our movies and exhibits and the lives of our visitors. This movie has been a real challenge. Since St. Louis is not on a coast, why should St. Louisians care about the sea? Or should they?

We need your help. We would like you to develop videos or books or give live performances in our galleries to share your ideas with our visitors on whether or not they should care about oceans, and why.

Students now know what they will be examining and the task they will be completing as a result of their research and investigation.

Students walk next door to the St. Louis Science Center to see *The Living Sea* to note any questions raised by the movie and to gather ideas that might help them meet the challenge.

Back at school, the whole team of four classes generates a list of questions it will need to answer to be able to address the dilemma: Should St. Louisians care about the ocean, why or why not? The team puts the questions into categories, and individual students choose a category to work on. Research groups of four to six students are formed by student preferences, with teachers making the final decision from their knowledge of the students.

One research group has come together to study endangered species of animals in the ocean. Its research takes the students to the library to review materials, to the World Wide Web through computers in the classroom to conduct searches for additional materials, to the St. Louis Zoo and the Mid-America Aquatic Center to gather more information on endangered aquatic species, and to their teachers for articles and direct instruction to assist them in their quest for answers and to learn more about how different media—short stories, poetry, movies—convey messages. Students participate in the Big Map program through the SLSC to learn more about the world's ocean and water system. Each resource provides some answers and sparks new questions. The teachers have established benchmarks and timelines for their research, but students want to keep going with their research when it is time to stop.

Once research groups have reached enough of a level of expertise, about halfway through the unit, students share what they have learned by jigsawing. One person from each research group joins representatives from each of the other research groups to form a new jigsaw group. With an expert from each

research topic, groups are now ready to work on the consequential task, going back to conduct additional research if needed.

One jigsaw group has decided as its consequential task to make a video for the SLSC. The members visit the traveling exhibition at the SLSC, *Special Effects: A Hands-On Exhibition* to learn more about how messages are conveyed through special effects. They work with the SLSC Producer to learn how to produce videos that demonstrate their understanding of the ocean. To be sure they use the results of their research and convey a clear message through their video, they work with teachers on their message. During the last two weeks of their unit, they produce their video, a newscast with scenes filmed at the SLSC and Compton-Drew.

COMMON PRINCIPLES OF INQUIRY AND RESEARCH

These two previous vignettes illustrate different settings, different audiences, different subjects, different disciplines, and different ages. We also offered two different ways of looking at inquiry: The Exploratorium exercise is based on interactive experiences with phenomena, that of the St. Louis Science Center on research with secondary sources.

We believe that a common thread runs throughout both programs, especially in the fundamental assumptions that each program brings to the design of the inquiry learning experience. While surface features may look different, we suggest that deep underlying structures are very similar and that together the two programs allow us to extrapolate principles that will be appropriate for many different environments, disciplines, and learning settings.

What Is Meant by Inquiry at The Exploratorium?

Fundamental to The Exploratorium's Institute for Inquiry is the notion of inquiry as a way to make sense of the natural world. Its method is to ask questions and answer them with the process skills of science.

Inquiry starts within a defined content rich with real-world phenomena. The learner begins by being curious about those phenomena. This curiosity gives rise to many questions, some of which provide entry points to investigation as well as potential pathways for answering them. Learners group into teams to pursue their questions with investigations that take time. There is subtle facilitation and scaffolding along the way at appropriate moments so that the locus of control is transferred from facilitator to learner through modeling. There are enough materials to support an ongoing investigation and many opportunities to share results by

discourse with others. All along the way investigators collaborate, talk, learn how to represent newly learned concepts, and discover how to use the process skills of science: observing, questioning, hypothesizing, predicting, investigating, interpreting, and communicating.

The definition of inquiry on The Exploratorium's World Wide Web site (Table 2) gives a synopsis of this process. This mode of inquiry is active, interactive, self-regulated, and collaborative. It is assumed that different groups will share the fruits of their labor with one another at appropriate moments and that the group builds up an interrelated body of expertise that moves in the direction of deep content principles.

TABLE 2. WHAT DO WE MEAN BY INQUIRY?

Inquiry is an approach to learning that involves a process of exploring the natural or material world, that leads to asking questions and making discoveries in the search for new understandings. Inquiry, as it relates to science education, should mirror as closely as possible the enterprise of doing real science.

The inquiry process is driven by one's own curiosity, wonder, interest or passion to understand an observation or solve a problem.

The process begins by the learner noticing something that intrigues, surprises, or stimulates a question. What is observed often does not make sense in relationship to the learner's previous experience or current understanding.

Action is then taken through continued observing, raising questions, making predictions, testing hypotheses, and creating theories and conceptual models. The learners must find their own idiosyncratic pathway through this process; it is hardly ever a linear progression, but rather more of a back and forth or cyclical series of events.

As the process unfolds more observations and questions emerge, giving occasion for deeper interaction and relationship with the phenomena—and greater potential for further development of understanding.

Along the way, the inquirer is collecting and recording data, making representations of results and explanations, drawing upon other resources such as books, videos, and colleagues.

Making meaning from the experience requires intermittent reflection, conversations and comparison of findings with others, interpretation of data and observations, and applying new conceptions to other contexts as one attempts to construct new mental frameworks of the world.

Teaching science using the inquiry process requires a fundamental reexamination of the relationship between the teacher and the learner whereby the teacher becomes a facilitator or guide for the learner's own process of discovery and creating understanding of the world.

Source: <http://www.exploratorium.edu/IFI/about/inquiry.html>

What Is Meant by Research in Schools for Thought and Fostering Communities of Learners?

Schools for Thought (SFT) integrates three foundational projects: *The Adventures of Jasper Woodbury* developed at Vanderbilt University, *CSILE (Computer Supported Intentional Learning Environments)* developed at the Ontario Institute for Studies in Education, and *Fostering Communities of Learners (FCL)* developed at the University of California - Berkeley. In addition to researchers at these three institutions, faculty at the University of Missouri - St. Louis, staff at the St. Louis Science Center, and SFT teachers across North America are part of the SFT Collaborative, funded by the James S. McDonnell Foundation.⁸

The SFT research cycle, as used at Compton-Drew ILC Middle School, is based largely on the FCL Principles given in Table 3. As was seen in the vignette, this research process involves generating questions around a rich content, categorizing those questions, looking for answers in self-selected small groups, sharing results of research with classmates, and sharing understanding with the larger community of learners through use of jigsawing and a consequential task, such as the video for the Living Sea unit. The cycle is not as linear as it might first appear. Students find that answers lead to more questions and sharing knowledge with others leads to more research. The emphasis is on dialogue all along the way. The subject is rich enough to support a variety of research groups, yet all research centers around the large topic selected at the beginning of the project and leads toward a consequential task. This task is authentic and allows students of differing expertise to bring together their knowledge and to demonstrate their understanding of the principles of science, or other content, underlying the central idea.

TABLE 3. FOSTERING COMMUNITIES OF LEARNERS PRINCIPLES

ACTIVE, STRATEGIC LEARNING**Systems and cycles**

- ▶ repetitive participant structures as part of a research-share-perform activity system

Metacognition

- ▶ awareness, intentional learning
- ▶ reflective practice

Dialogic base

- ▶ shared discourse, negotiation of meaning
- ▶ seeding, migration, and appropriation of ideas

Distributed expertise

- ▶ individual and group expertise
- ▶ diversity, legitimization of differences

Multiple zones of proximal development

- ▶ mutual appropriation
- ▶ guided practice, guided participation

Community of practice

- ▶ shared community values
- ▶ respect, responsibility

Contextualized and situated

- ▶ purpose for activity
- ▶ intellectually honest curriculum
- ▶ transparent and authentic assessment

Source: Ash, 1995 adapted from Brown & Campione, 1994

Inquiry and Research: Equivalent Forms in Different Settings

Inquiry as described by the Institute for Inquiry and research as described in the Compton-Drew example share similar underlying principles. We support this by highlighting commonalities between both programs and by identifying theoretical principles that others might use in their design. These principles allow us to move towards providing a practical template for learning environment design.

Part of the strength of the argument for commonality between inquiry and research is that even though the programs differ in context and learning setting,

they map onto each other in significant ways. FCL/SFT is heavily steeped in L. S. Vygotsky's (1978) concept of zones of proximal development (ZPD)—the area between a child's current abilities and the distance she can traverse with the aid of a more capable peer or teacher—using a variety of participant structures (Brown et al., 1993) designed to create multiple opportunities for classroom learning. At the Institute for Inquiry, inquiry is strongly rooted in curiosity and personal interaction with generative phenomena. And although inquiry can have a variety of interpretations, this cyclic process has a structure and essential elements that characterize it. The learner is engaged with compelling content while using process skills to investigate self-selected questions. Scaffolding of skills and strategies is an essential for translation to classroom settings. Foundational elements—how to use the process skills of science, how to think metacognitively, how to share results with others—need to be modeled. Once laid down as foundation, these skills help build ownership and competence for inquirers and a sense of accomplishment in moving towards independent investigations (Ash, 1999).

We have isolated ten principles common to both programs. They provide a framework beginning to build inquiry programs in many settings.

1. **Delimited content.** Inquirers and researchers move toward a richly generative content that has well-defined principles. Sample conceptual principles might include the independence of ecosystems, as in the Living Sea unit at Compton-Drew, or understanding the interrelationship between color light and color pigment, considered in the Institute for Inquiry.
2. **Research and inquiry are controlled by the learner.** The inquiry question, the nature of the research, the object of inquiry have been determined, at least partially, by the learners, in a group of from two to five. Ideally, the locus of control is gradually given to the learners as they gain competence.
3. **Group meaning making.** As they build an understanding of big ideas, learners engage in group making of meaning. This building of knowledge contributes to the community's knowledge base, which continues to grow as learners share results of their inquiries.
4. **The process of inquiry and research is repetitive, cyclic, and open-ended.** An iterative research or inquiry cycle allows the learner to use the processes of science over and over again, in non-linear fashion. The cycle is somewhat open-ended, allowing many possible direc-

tions and many possible different answers. Research and inquiry often end with more questions. (See Brown & Campione, 1996; White & Frederiksen, in this volume.)

5. **The processes and skills are the same.** The processes of observing, raising questions, making predictions, posing hypotheses, investigating and gathering information, interpreting, and communicating are the same (Harlen & Jelly, 1997).
6. **The cycles are similar.** The research or inquiry cycle begins with curiosity and questioning in the exploration phase. As it continues, there is a deep involvement in a particular set of questions generated by the learners. There can be confusion, redirection, and re-posing of hypotheses and questions. The cycle culminates with teaching and sharing results and interpretations.
7. **Collaborative learning.** Children and adults work together to create a larger understanding. In such a community of learners, everyone knows different parts of the overall topic; creating distributed expertise (Brown et al., 1993; Bereiter & Scardamalia, 1993). Everyone's work is an essential component of the whole group's making of meaning.
8. **Active, strategic learning.** Learners are expected to interact on an ongoing basis with one another, with resources and with phenomena. Learners move beyond hands-on interactions to engagement with one another and the objects of inquiry.
9. **Metacognitive.** At regular checkpoints, learners are asked to reflect upon what they know and what they still need to find out in light of theirs and others' work (Palinscar & Brown, 1984; Bruer, 1993). Learners become aware of their own understanding and know why certain strategies facilitate their learning.
10. **Dialogic.** In order to make sense, learners communicate, have information to share and need the information from others. Thus, learning and teaching become reciprocal activities for everyone involved (Brown et al., 1993; Lemke, 1990).

PUTTING IT ALL TOGETHER

Practical Issues

We next need to consider how these ten principles can help us design an inquiry classroom. We know that inquiry can take on many different looks that depend on the classroom context, the age of students, the disciplinary content, and of course the level of experience of the teacher and the students. A teacher new to inquiry may approach design differently from another more experienced. At the beginning of classroom inquiry, for example, the teacher typically helps her students learn the skills basic to doing independent inquiry. She may take time to develop questioning skills or different ways to interpret evidence. We argue, however, that most inquiry classrooms will eventually embody some aspects of the basic principles we have outlined. We suggest that these principles can be met in any number of practical ways, from simple to more complex and that there are incremental steps toward complex inquiry or research.

Amidst the difficulties of the average classroom, how might a teacher apply the ten principles? This chapter lacks the space to do more than begin to address these issues. Table 4 provides a working model of an inquiry path framed by the practical and social constraints critical to the average classroom. We know full well that this is only the beginning of a model that might be used in a variety of instantiations (Ash, 1999).

Social Context. Of the many aspects of the social context that the ten principles address, two elements deserve special emphasis here: the ethos of questioning, of not knowing the answers; and the notion of scaffolding within the zone of proximal development.

An Ethos of Questioning. The social dynamic is driven by the learner's curiosity: questioning is critical to forming a community of learners. Together learners form a social unit that investigates a series of related questions. Taken together, the results of the inquiry will create a whole that is bigger than any individual piece. Within the community, facilitators are curious learners with questions of their own. Curiosity followed by questioning is the underpinning of a community of inquiry. There needs to be a genuine honoring of "not knowing" and a trust that there are steps toward finding out.

Scaffolding. Scaffolding implies gradually transferring ownership of the inquiry process to the learner. Though facilitators are not willing to give the answers without investigation on the part of the learner, they are ready to model the inquiry path themselves. Facilitation is subtle, but ever-present. Knowing when to intervene and scaffold is a critical factor for those in charge. Asking

open-ended questions to guide the learners becomes an important technique in shifting the locus of control toward the learner. In the beginning the facilitator gives more guidance, more modeling. Gradually, as the learner gains competence, the facilitator pulls back increasingly.

**TABLE 4. WORKING MODEL OF INQUIRY PATH
IN AN AVERAGE CLASSROOM**

SOCIAL CONTEXT	CURIOSITY AROUSED	PRACTICAL CONTEXT
Driven by learner	Learners pose questions and choose pathway	Delimited content area
Collaborative learning	Observation	Formative and summative assessment
Ethos: Questioning as a habit of mind	Hypotheses	Assorted, rich materials to invite inquiry
Active, strategic learning	Gathering data	Physical environment
Dialogic	Predicting	Time
Metacognition: Knowing what you know	Interpreting	Multiple entry points
Group making of meaning	Testing ideas	Facilitation
	Communication and reporting to others	Moving toward big ideas

Practical Context. The practical context creates an environment that supports the inquiry path. In designing this environment, the content of the inquiry, assessment, materials, physical space, location, and time must be considered.

Assessment. In research and inquiry, assessment might take the form of examining the students' understanding in an ongoing and formative fashion. Facilitators can assess the students' prior knowledge early on. Student self assessment can occur throughout as groups receive feedback from their peers and teachers. This type of assessment becomes continuous and integral to the process of moving toward deeper understanding of the big ideas of science. Assessing formatively allows the facilitator to change her actions in response to student needs (Vermont Elementary Science Project, 1995; Brown & Shavelson, 1996; Harlen, 1999).

Materials. Materials that are easily accessible and visible to learners invite their curiosity. They should be well planned in advance. There will be enough to get started but also more available to invite further questioning. Materials need not be expensive and many of them can come from the students. Resources and the results of inquiry collected from one class can serve as a foundation for resources for the next semester or year. Materials that are easily accessible and visible to learners invite their curiosity.

Physical Environment. Inquiry can be messy and require a large space. The ideal classroom will be large, easy to clean, and sturdy. Chairs and tables will be arranged in variety of configurations by learners to support their work.

Time. Time to spend in an inquiry process over an extended period is critical. One forty-five minute period is not enough. Block scheduling and stretching the inquiry over weeks provide more time for meaningful inquiry.

GETTING STARTED/RESOURCES⁹

To assist the reader's own inquiry into building the synergy between formal and informal learning and environments, we offer a variety of resources as starting points. (See Table 5.) We hope these will lead to additional resources, additional questions, and new understandings.

TABLE 5. RESOURCES FOR BUILDING SYNERGY BETWEEN FORMAL AND INFORMAL LEARNING AND ENVIRONMENTS

COMMUNITIES OF LEARNERS

Brown & Campione, 1994. Guided discovery in a community of learners.

Brown & Campione, 1996. Psychological theory and the design of learning environments: On procedures, principles and systems.

Matusov & Rogoff, 1995. Evidence of development from people's participation in communities of learners.

DISTRIBUTED EXPERTISE

Brown, Ash, et al., 1993. Distributed expertise in the classroom.

Scardamalia & Bereiter, 1996. Engaging students in a knowledge society.

INTRINSIC MOTIVATION

Csikszentmihalyi & Hermanson, 1995. Intrinsic motivation in museums: Why does one want to learn?

INQUIRY AND LEARNING WEBSITES

Exploratorium Institute for Inquiry—<http://www.exploratorium.edu/IFI/>
 Museum Learning Collaborative annotated bibliographies –
<http://mlc.lrdc.pitt.edu/mlc/>

Center for Museum Studies' database with search capabilities –
<http://www.si.edu.organiza/offices/musstud/data.htm>

MUSEUM EDUCATION

Hein & Alexander, 1998. *Museums: Places of learning.*

Mann, 1997. Extending the curriculum through museums.

MUSEUM SCHOOLS

Klein, 1998. Putting theory into practice: Compton-Drew investigative learning center.

Science Museum of Minnesota, 1995. Case studies of five museum schools.

SCIENCE CENTERS, MUSEUMS, AND OTHER INFORMAL LEARNING ENVIRONMENTS WEBSITES

American Museum of Natural History – <http://www.amnh.org>

Boston Museum of Science – <http://www.mos.org>

The Exploratorium – <http://www.exploratorium.edu>

The Field Museum – <http://www.fnmh.org>

Franklin Institute – <http://www.fi.edu>

Informal Learning Environments Research SIG –

<http://darwin.sesp.nwu.edu/informal/>

Lawrence Hall of Science – <http://www.lhs.berkeley.edu>

Missouri Botanical Gardens – <http://www.mobot.org>

New York Hall of Science – <http://www.nyhallsci.org>

Ontario Science Center – <http://www.osc.on.ca>

Science Museum of Minnesota – <http://www.sci.mus.mn.us>

St. Louis Science Center – <http://www.slsc.org>

St. Louis Zoo – <http://www.stlzoo.org>

We hope you, the reader, have gained new perspectives on the potential synergy between informal and formal learning environments. We hope this chapter caused you to generate your own questions about how inquiry can build on this synergy in your own practice. Finally, we hope you will continue your inquiry as you put these principles into practice.

ENDNOTES

1. In the vignettes and throughout this chapter, each author wrote from her own experience with formal and informal learning environments and with inquiry and research. Doris Ash is a science educator at The Exploratorium in San Francisco working with the Institute for Inquiry for teachers and administrators new to the inquiry process and the Professional Development Design Workshop for those who will lead others in designing workshops and curriculum based in inquiry. Doris has worked with teachers and students involved in the Fostering Communities of Learners project in the Bay Area since it began in 1989. Christine Klein, Investigative Learning Center (ILC) Program Manager for the St. Louis Science Center, works with students and teachers at the Compton-Drew ILC Middle School, a museum school in partnership with St. Louis Public Schools that uses the Schools for Thought curriculum framework. Both authors are working toward building the synergistic relationship between formal and informal learning discussed in this chapter.

2. Funding agencies like the National Science Foundation began to use the term “informal” to support projects outside “formal” classroom settings. They include public television and community organizations as informal settings. These last two settings are not the focus of this chapter.
3. Schools for Thought, described later in the chapter, provides the theoretical framework and philosophy for the program at Compton-Drew Middle School. The curriculum described in this chapter was designed by Science Center staff within that framework.
4. For further discussion of distinctions and definitions of informal and formal, see “ILER Forum: How Do We Define Ourselves?” in the *Informal Learning Environments Research Newsletter*, February 1998, available from the Informal Learning Environments Research special interest group of the American Educational Research Association or on the group’s website, <http://darwin.sesp.nwu.edu/informal/>.
5. For more information on museum schools, see Science Museum of Minnesota 1995 and the issue of the *Journal of Museum Education* (vol. 23, no. 2, 1998) on museum and school partnerships.
6. A jigsaw group is formed by taking one expert from each research group to form a new group in which each expert has a key piece of the puzzle to share (Aronson, 1978).
7. The longer version of this case study was presented at the Institute of Inquiry Forum in 1996.
8. For more information on these projects, see Bruer, 1993; Lamon et al., 1996; and McGilly 1994.
9. Complete citations for publications are in reference section.

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The Need for Special Science Courses for Teachers: Two Perspectives

Lillian C. McDermott and Lezlie S. DeWater*

A physics professor and a classroom teacher present their perspectives on the type of preparation that K-12 teachers need in order to be able to teach science as a process of inquiry. Both have had more than twenty-five years of experience in teaching at their respective levels and in working with precollege teachers. Although the context for much of the discussion is physics, analogies to other sciences can readily be made.

THE PERSPECTIVE OF A PHYSICS PROFESSOR

In the United States, precollege teachers are educated in the same universities and colleges as the general population. In most institutions, two independent administrative units are involved: a college or school of education that offers courses on the psychological, social, and cultural aspects of teaching, and a college of arts and sciences (or equivalent) that provides instruction in various disciplines. Whereas the preparation of K-12 teachers may be central to faculty in education, such a function is often considered peripheral to the mission of a science department. Most faculty in the sciences take the position that responsibility for the professional development of teachers resides solely within colleges of education.

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This point of view ignores the fact that almost all the instruction that precollege teachers receive in the sciences takes place in science departments. If the current national effort toward reform in K-12 science education is to succeed, science faculty must take an active role in the preparation of teachers in their disciplines.

The perspective of the physics professor that is presented here is based on the cumulative experience of the Physics Education Group at the University of Washington.¹ For many years, the group has been conducting research on the learning and teaching of physics and using the results to guide the development of curriculum for various student populations at the introductory level and beyond.² In addition to participating in the regular instructional program in the Department of Physics, the group has been conducting intensive programs for in-service teachers during the summer and for both preservice and in-service teachers during the academic year. This experience has provided a structure for the ongoing development and assessment of *Physics by Inquiry*, a laboratory-based curriculum designed to prepare K-12 teachers to teach physics and physical science as a process of inquiry.³ The group is also producing a research-based supplementary curriculum to help improve student learning in introductory physics.⁴

Inadequacy of Traditional Approach

Science departments offer a number of courses that can be taken by prospective teachers. Some of these courses may be required for certification to teach a particular science in high school. Others may be taken by future elementary and middle school teachers to satisfy a general science requirement for graduation. Some departments also offer short survey courses that they recommend for teachers. As the discussion below in the context of physics illustrates, this traditional approach does not work well for preparing teachers at the elementary, middle, or high school levels.

Many physics faculty seem to believe that the effectiveness of a high school teacher will be determined by the number and rigor of physics courses taken. Accordingly, the usual practice is to offer the same courses to future high school teachers as to students who expect to work in industry or enter graduate school. That overlooks the character of K-12 teaching.

The content of the high school curriculum in physics is closely matched to the first-year in college. However, the first-year college course is not adequate preparation for teaching the same material in high school. The breadth of topics covered allows little time for acquiring a sound grasp of the underlying concepts. The routine problem solving that characterizes most introductory courses does not

help teachers develop the reasoning ability necessary for handling the unanticipated questions that are likely to arise in a classroom. The laboratory courses offered by most physics departments do not address the needs of teachers. Often the equipment is not available in the teachers' schools, and no provision is made for showing them how to plan laboratory experiences that make use of simple apparatus. A more serious shortcoming is that experiments are mostly limited to the verification of known principles. Students have little opportunity to start from their observations and go through the reasoning involved in formulating principles. As a result, it is possible to complete the laboratory course without confronting conceptual issues or understanding the scientific process.

For those students who progress beyond the first year of university physics, advanced courses are of little direct help in teaching. The abstract formalism that characterizes upper division courses is not of immediate use in the precollege classroom. Sometimes in the belief that teachers need to update their knowledge, university faculty may offer courses on contemporary physics for preservice or in-service teachers. Such courses are of limited utility. The information may be motivational but does not help the teachers recognize the distinction between a memorized description and substantive understanding of a topic. Although work beyond the introductory level may help teachers deepen their understanding of physics, no guidance is provided about how to make appropriate use of this knowledge in teaching high school students.

Elementary and middle school teachers often lack the prerequisites for even the standard introductory courses, especially in the physical sciences. They are unlikely to pursue the study of any science in depth because the vertical structure of the subject matter requires progression through a prescribed sequence of courses. In physics, in particular, the need for mathematical facility in the standard courses effectively excludes those planning to teach below the high school level. The only courses generally available are almost entirely descriptive. A great deal of material is presented, for which most preservice and in-service teachers (as well as other students) have neither the background nor the time to absorb. Such courses often reinforce the tendency of teachers to perceive physics as an inert body of information to be memorized, not as an active process of inquiry in which they and their students can participate.

The total separation of instruction in science (which takes place in science courses) from instruction in methodology (which takes place in education courses) decreases the value of both for teachers. Effective use of a particular instructional strategy is often specific to the content. If teaching methods are not studied in the context in which they are to be implemented, teachers may be unable

to identify the critical elements. Thus, they may not be able to adapt a strategy that has been presented in general terms to specific subject matter or to new situations. Detailed directions in teacher's guides are of little use when teachers do not understand either the content or the intended method of presentation.

The traditional approach to teacher preparation in science departments has another major shortcoming. Teachers tend to teach as they have been taught. If they were taught through lecture, they are likely to lecture, even if this type of instruction may be inappropriate for their students. Many teachers cannot, on their own, separate the physics they have learned from the way in which it was presented to them.

Development of Special Physics Courses for Teachers

To counter the public perception that physics is extremely hard, a teacher must be able to teach in a way that allows students to achieve adequate mastery of a topic and to develop the confidence necessary to apply this knowledge in daily life. Since neither traditional physics courses nor professional education courses provide this type of preparation, there is a need for special physics courses for teachers.^{1,5}

An effort to meet this need led to the establishment by A.B. Arons in 1968 of a course for preservice elementary school teachers in the Department of Physics at the University of Washington.⁶ Shortly after, preservice courses for middle and high school teachers were added.^{7,8} In-service versions soon followed. Modifications of the original courses constitute the core of the present teacher preparation program of the Physics Education Group. The preservice courses, which are supported by the department, are taught during the academic year. The inservice program consists of an intensive, six-week National Science Foundation summer institute for K-12 teachers and a continuation course that meets weekly during the academic year. Most teachers enroll for more than one year.

In addition to their instructional function, the preservice and in-service courses have provided a context for research on the learning and teaching of physics, as well as a setting for the development of *Physics by Inquiry*. Presented here is a distillation of what we have learned about the preparation of teachers and what we have tried to incorporate in our curriculum. The discussion is not an exhaustive summary of all that should be done. For example, important practical matters, such as laboratory logistics and classroom management, are not addressed. The focus is on intellectual aspects.

Intellectual Objectives

The curriculum used in courses for teachers should be in accord with the instructional objectives. The emphasis should be on the content that the teachers are expected to teach. They need the time and guidance to learn basic physics in depth, beyond what is possible in standard courses. Teachers should be given the opportunity to examine the nature of the subject matter, to understand not only what we know, but on what evidence and through what lines of reasoning we have come to this knowledge. Conceptual understanding and capability in scientific reasoning provide a firmer foundation for effective teaching than superficial learning of more advanced material.

A primary intellectual objective of a course for teachers should be a sound understanding of important concepts. Equally critical is the ability to do the qualitative and quantitative reasoning that underlie the development and application of concepts. Instruction for teachers should cultivate scientific reasoning skills, which tend to be overlooked in traditional courses. It has been demonstrated, for example, that university students enrolled in standard physics courses often cannot reason with ratios and proportions.⁹ Proportional reasoning is obviously a critically important skill for high school science teachers, but it is also essential for elementary and middle school teachers who are expected to teach science units that involve concepts such as density and speed.

The emphasis in a course for teachers should not be on mathematical manipulation. Of course, high school teachers must be able to solve textbook problems. As necessary as quantitative skills are, however, ability in qualitative reasoning is even more critical. Courses for teachers should avoid algorithmic problem solving. Questions should be posed that require careful reasoning and explanations. Teachers need to recognize that success on numerical problems is not a reliable measure of conceptual development. It is also necessary for them to develop skill in using and interpreting formal representations such as graphs, diagrams, and equations. To be able to make the formalism of physics meaningful to students, teachers must be adept at relating different representations to one another, to physical concepts, and to objects and events in the real world.

An understanding of the nature of science should be an important objective in a course for teachers. Teachers at all grade levels must be able to distinguish observations from inferences and to do the reasoning necessary to proceed from observations and assumptions to logically valid conclusions. They must understand what is considered evidence in science, what is meant by an explanation, and what the difference is between naming and explaining. The scientific process

can only be taught through direct experience. An effective way of providing such experience is to give teachers the opportunity to construct a conceptual model from their own observations. They should go step by step through the process of making observations, drawing inferences, identifying assumptions, formulating, testing, and modifying hypotheses. The intellectual challenge of applying a model that they themselves have built (albeit with guidance) to predict and explain progressively complex phenomena can help teachers deepen their own understanding of the evolving nature, use, and limitations of a scientific model. We have also found that successfully constructing a model through their own efforts helps convince teachers (and other university students) that reasoning based on a coherent conceptual framework is a far more powerful approach to problem solving than rote substitution of numbers in memorized formulas.

The instructional objectives discussed above are, in principle, equally appropriate for the general student population. However, teachers have other requirements that special physics courses should address. For example, teachers need practice in formulating and using operational definitions. To be able to help students distinguish between related but different concepts such as between velocity and acceleration, teachers must be able to describe precisely and unambiguously how the concepts differ and how they are related. It is important that teachers be able to express their thoughts clearly. Discussions and writing assignments that require them to reflect on the development of their own conceptual understanding of a particular topic can enhance both their knowledge of physics and their ability to communicate.

In addition to having a strong command of the subject matter, teachers need to be aware of difficulties that students encounter in studying specific topics. There has been a considerable amount of research on difficulties common to students at all levels (K-20) of physics education.¹⁰ Instructors in courses for teachers should be thoroughly familiar with this resource and, when appropriate, refer them to the literature.

Courses for teachers should also help develop the critical judgment necessary for making sound choices on issues that can indirectly affect the quality of instruction in the schools. Teachers must learn, for example, to discriminate between meaningful and trivial learning objectives. When instruction is driven by a list of objectives that are easy to achieve and measure, there is danger that only shallow learning such as memorization of factual information will take place. Teachers need to develop criteria for evaluating instructional materials, such as science kits, textbooks, laboratory equipment, and computer software. They should be able to identify strengths and weaknesses in school science pro-

grams. Aggressive advertising and an attractive presentation often interfere with objective appraisal of the intellectual content of printed materials or computer software. We have seen teachers react with enthusiasm to an appealing program format, while they ignore serious flaws in physics. Through service on district committees, individual teachers can often have an impact that extends beyond their own classrooms. A poor curriculum decision can easily deplete the small budget most school districts have for science without resulting in an improvement in instruction.

Instructional Approach

If the ability to teach by inquiry is a goal of instruction, then teachers need to work through a substantial amount of content in a way that reflects this spirit. Teachers should be prepared to teach in a manner that is appropriate for the K-12 grades. Science instruction for young students is known to be more effective when concrete experience establishes the basis for the construction of scientific concepts.¹¹ We and others have found that the same is true for adults, especially when they encounter a new topic or a different treatment of a familiar topic. Therefore, instruction for prospective and practicing teachers should be laboratory-based. However, “hands-on” is not enough. Unstructured activities do not help students construct a coherent conceptual framework. Carefully sequenced questions are needed to help them think critically about what they observe and what they can infer. When students work together in small groups, guided by well-organized instructional materials, they can also learn from one another.

Whether intended or not, teaching methods are learned by example. The common tendency to teach physics from the top down, and to teach by telling, runs counter to the way precollege (and many university) students learn best. The instructor in a course for teachers should not transmit information by lecturing, but neither should he or she take a passive role. The instructor should assume responsibility for student learning at a level that exceeds delivery of content and evaluation of performance. Active leadership is essential, but in ways that differ markedly from the traditional mode. This approach, which can be greatly facilitated by a well-designed curriculum, is characterized below in general terms and illustrated in the next section in the context of specific subject matter. Other examples are given in published articles.¹²

The instructional materials used in a course for teachers should be similar to those used in K-12 science programs, but the curriculum should not be identical. Teachers must have a deeper conceptual understanding than their students

are expected to achieve. They need to be able to set learning objectives that are both intellectually meaningful for the topic under study and developmentally appropriate for the students.

The study of a new topic should begin with open-ended investigation in the laboratory, through which students can become familiar with the phenomena of interest. Instead of introducing new concepts or principles by definitions and assertions, the instructor should set up situations that suggest the need for new concepts or the utility of new principles. By providing such motivation, the instructor can begin to demonstrate that formation of concepts requires students to become mentally engaged. Generalization and abstraction should follow, not precede, specific instances in which the concept or principle may apply. Once a concept has been developed, the instructor should present new situations in which the concept is applicable but may need to be modified. This process of gradually refining a concept can help develop an appreciation of the successive stages that are involved in developing a sound conceptual understanding.

As students work through the curriculum, the instructor should pose questions designed to help them to think critically about the subject matter and to ask questions on their own. The appropriate response of the instructor to most questions is not a direct answer but another question that can help guide the students through the reasoning necessary to arrive at their own answers. Questions and comments by the instructor should be followed by long pauses in which the temptation for additional remarks is consciously resisted. Findings from research indicate that the quality of student response to questions increases significantly with an increase in “wait time,” the time the instructor waits without comment after asking a question.¹³

As mentioned earlier, a course for teachers should develop an awareness of common student difficulties. Some are at such a fundamental level that, unless they are effectively addressed, meaningful learning of related content is not possible. Serious difficulties cannot be overcome through listening to lectures, reading textbooks, participating in class discussions, or consulting references (including teacher’s guides). Like all students, teachers need to work through the material and have the opportunity to make their own mistakes. When difficulties are described in words, teachers may perceive them as trivial. Yet we know that often these same teachers, when confronted with unanticipated situations, will make the same errors as students. As the opportunity arises during the course, the instructor should illustrate instructional strategies that have proved effective in addressing specific difficulties. If possible, the discussion of a specific strategy should occur only after it has been used in response to an error. Teachers are

much more likely to appreciate important nuances through an actual example than through a hypothetical discussion. Without specific illustrations in the context of familiar subject matter, it is difficult for teachers to envision how to translate a general pedagogical approach into a specific strategy that they can use in the classroom. The experience of working through the material themselves can help teachers identify the difficulties their students may have. Those who understand both the subject matter and the difficulties it poses for students are likely to be more effective than those who know only the content.

Illustrative Example

To illustrate the type of instruction discussed above, we present a specific example based on a topic included in many precollege programs: batteries and bulbs. Below we describe how students, including preservice and in-service teachers, are guided to develop a conceptual model for a simple dc circuit.¹⁴ Mathematics is not necessary; qualitative reasoning is sufficient.

The students begin the process of model-building by trying to light a small bulb with a battery and a single wire. They develop an operational definition for the concept of a complete circuit. Exploring the effect of adding additional bulbs and wires to the circuit, they find that their observations are consistent with the assumptions that a current exists in a complete circuit and the relative brightness of identical bulbs indicates the relative magnitude of the current. As the students conduct further experiments—some suggested, some of their own devising—they find that the brightness of individual bulbs depends both on how many are in the circuit and on how they are connected to the battery and to one another. The students are led to construct the concept of electrical resistance and find that they can predict the behavior of many, but not all, circuits of identical bulbs. They recognize the need to extend their model beyond the concepts of current and resistance to include the concept of voltage (which will later be refined to potential difference). As bulbs of different resistance and additional batteries are added, the students find that they need additional concepts to account for the behavior of more complicated circuits. They are guided in developing more complex concepts, such as electrical power and energy. Proceeding step by step through deductive and inductive reasoning, the students construct a conceptual model that they can apply to predict relative brightness in any circuit consisting of batteries and bulbs.

We have used this guided inquiry approach with teachers at all educational levels from elementary through high school. The process of hypothesizing,

testing, extending, and refining a conceptual model to the point that it can be used to predict and explain a range of phenomena is the heart of the scientific method. It is a process that must be experienced to be understood.

It is important that teachers be asked to synthesize what they have learned, to reflect on how their understanding of a particular topic has evolved, and to try to identify the critical issues that need to be addressed for meaningful learning to occur. They also need to examine the interrelationship of topics in the curriculum in order to be able to teach science in a coherent manner. Through direct experience with the intellectual demands of learning through inquiry, teachers can become better equipped to meet the challenge of matching their instruction to the developmental level of their students. We have found that the sense of empowerment that results from this type of preparation helps teachers develop confidence in their ability to deal with unexpected situations in the classroom.

THE PERSPECTIVE OF A CLASSROOM TEACHER

In this section, an elementary school teacher describes her early days as a teacher and the impact of the type of instruction described above on her professional development. Today, more than 25 years later, she reflects on how this experience has affected the way in which she teaches science in her classroom.

I earned my B.A. with a major in French and a minor in elementary education. I had initially intended to be a high school teacher but at the eleventh hour changed my mind, hoping that my 5' 3" stature might put me above the eye level of most elementary students. With my diploma and certificate in hand, I was confident that I knew at least as much English and mathematics as a sixth grader, certain that I could learn the rest from the teacher's guides for the student textbooks. I applied for only one position and was promptly hired by a large urban school district as a second-grade teacher. All went as I had expected. I knew more than the second graders and was quick to employ all that I had learned in my first eight years of education—teaching, of course, in the same manner in which I had been taught in a crowded Catholic school classroom. I did, however, make some attempts to form small groups for reading. I felt very fortunate that my class of twenty-eight students was twenty fewer than the classes that I had experienced as a child.

In late spring of my first year of teaching, I was informed that a drop in enrollment would result in the elimination of the position that I held. The good news was that I was welcome to take a newly created position as the science specialist for grades K-4. Not wanting to relocate and not stopping to consider that

my major in French might not have appropriately prepared me for this new position, I quickly agreed to take it for the following year. Shortly after I accepted the job, the district science supervisor contacted me, suggesting we start with a couple of *Elementary Science Study* units, “Clay Boats” and “Primary Balancing.”¹⁵ The unit guides and equipment were ordered. I was all set to begin my new teaching role.

Never having had a science lesson in elementary school, I was not predisposed, as I had been with the other subjects, to teach it as I had been taught. In fact, without any real textbook to guide the students, I was left with the materials and a few rather general instructions in the teacher’s guide. And so it was that we, my students and I, became explorers of materials. We had a great time. The students were engaged; they talked a lot about what they were doing and we all asked a lot of questions. But I wanted to do more than just explore and ask questions. I wanted to learn some basic principles and have a clear vision of where we were going. I wanted to lead my students to discover and understand something as well. But what was it that we should be understanding? I hadn’t a clue. This is when I first came to recognize that to become a truly effective teacher, I would need scientific skills and understandings that I had not developed, nor been required to develop, during my undergraduate years.

Not long after I recognized my deficiencies, I happened to glance through the school district’s newsletter and came across a notice for a National Science Foundation Summer Institute in Physics and Physical Science for Elementary Teachers. I had been turned down the previous year for lacking sufficient teaching experience. I was certain that they would now recognize that I did not know enough science to teach. I was right; this time I was accepted.

I walked away from that summer feeling that my brain had been to boot camp. No course of study, no teacher, had ever demanded so much of me. I had never before been asked to explain my reasoning. A simple answer was no longer sufficient. I had been expected to think about how I came to that answer and what that answer meant. It had been excruciating at times, extricating the complicated and detailed thought processes that brought me to a conclusion, but I found it became easier to do as the summer progressed. I realized that it was not only *what* I learned but also *how* I learned that had provided me with new-found self esteem and confidence. The carefully sequenced questions had helped me come to an understanding of science that I had always felt was beyond me. I wanted to be able to lead my students to that same kind of understanding. It became clear to me that the key to teaching by inquiry was first understanding the content myself.

As a result of the Summer Institute, I had developed a sound understanding of several basic science concepts including balance, mass, and volume. Along with these concepts I discovered an appreciation for the need to control variables in an experiment. I was now better equipped to take a more critical look at the science units I had used the previous year. I recognized that “Clay Boats” had probably not been the best choice for a teacher with only a budding understanding of sinking and floating, but “Primary Balancing” seemed to be an appropriate choice. I had worked with very similar materials in the Summer Institute and had some ideas about how I could lead students to discover, through experiments in which they would come to understand the need to control variables, which factors seem to influence balance and which do not.

Unlike many of the professional development courses that I have taken since that time, the Summer Institute was certainly not in the category “*been there, done that.*” I had been there, but there was still so much I hadn’t done, so much I felt I needed and wanted both to do and to learn. Science, with all the skills and concepts that term connotes, is an overwhelming body of knowledge. You just scratch the surface and you find that what lies underneath extends much deeper than you had ever anticipated. It is for this reason that I felt compelled to return. And so I did, again and again and again. I participated in several Summer Institutes and academic year continuation courses, both as a student and as a member of the instructional staff. Assimilation is not a process to be rushed, nor is application. It must be thoughtful. It must be deliberate. It must be evaluated. The process takes time, lots of time. Time that we as teachers have difficulty finding. Time that administrators are reluctant to relinquish.

After many years of professional development in science education, I feel comfortable teaching most, if not all, of the science concepts covered in elementary and middle school. An understanding of the content allows me to teach with confidence units such as electric circuits, magnetism, heat and temperature, and sinking and floating. But simply understanding the content did not assure that I could bring my students to an understanding appropriate for them.

How does one begin to develop some expertise in these strategies we call inquiry? I can only suppose that for me it began by reflecting upon my personal experience. I don’t believe that this was a deliberate exercise on my part. In subtle ways, over many years, I began to teach in the manner in which I had been taught in the Summer Institutes.

I know that early on I began to pay attention to the questions that I asked, for the questions stood out in my mind as the tools that, when deftly wielded, resulted in the desired state of understanding. I knew, too, that questions would help

me to discover the intellectual status of my students: to tell me where they were with the necessary conceptual understanding. Aware of several “pitfalls” (misconceptions) that I had personally encountered, I was prepared to think about questions that would help me find out where I needed to start. I envisioned the terrain between the students and their conceptual understanding. I liken the terrain to an aerial photograph that clearly details the various roads that lead to the designated destination, along with dead ends and the hazards. I am well acquainted with this terrain, because I have traversed it on more than one occasion myself, and have conversed with others who have, perhaps, taken a different path to the same destination. I want my students to encounter some difficulties and to resolve conflicts and inconsistencies and to grow intellectually from these experiences. But I do not want them to wander aimlessly or to plunge over a cliff. For this reason it is crucial that, like a vigilant parent, I continue to offer support in their intellectual insecurity. I question and listen carefully. I scan the territory to find where the explanations and responses to my questions place them, and then plan my next strategy to keep them moving ahead. I recall from being a learner that sometimes this next strategy is a question such as, “What would you need to do to find out?” Sometimes it is a suggestion of some experiment to try. Sometimes it is a comment such as, “Why don’t you think about that for a bit.” It has taken many years of trying out these strategies to learn how to gauge which tactic is appropriate at what time and with which student.

There are, of course, other considerations in the teaching of inquiry-based science that must accompany all that I have said. It is necessary to think about the engagement of students and developmental appropriateness. For the elementary school students with whom I have worked, engagement has never been a problem. Science is naturally engaging if the teacher shows the least bit of enthusiasm. Students are intrigued by the world around them and have already begun to develop their own explanations for how and why Mother Nature operates in the way she does. The trick is to capitalize on this curiosity and channel it so that students develop better explanations for basic phenomena.

The question of developmental appropriateness is another matter. I have come to a much clearer recognition of what will “fly” and what will not, as a result of working through *Physics by Inquiry* in the Summer Institutes.³ These materials were carefully designed to build conceptual understanding in logical, sequential steps. You do not, for instance, begin to think about why things sink or float without first understanding by concrete operational definitions what is meant by mass and what is meant by volume. Only then can you begin to think about how these two variables may influence sinking and floating. I have also

come to appreciate the difficulty of these concepts for the adult learner. I think long and hard about the research that gives us some notion of what children of a particular age are capable of doing. Although I may explore the concepts of mass and volume with eight- and nine-year olds, I certainly would not expect most of them to come to an understanding of density. I will sometimes stretch the limits slightly, knowing that we may not really know how far each student can go. Elementary school teachers have not had a great track record for teaching science to their students, but I believe that if we structure what we teach more carefully, we can do better. After all, who would have thought that a high-school-bound French teacher would come to understand a relatively large body of physical science, including physics?

In summary, I would like to repeat that what seems to have been most important for me in becoming a more effective teacher of science at the elementary level was both to gain a sound understanding of the content and to learn it through inquiry-based instruction. It was then necessary to reflect explicitly on my experience as a learner so that I could put into practice what had been modeled for me.

CONCLUSION

Significant improvement in the learning of science by elementary, middle, and high school students can take place only when the problem of inadequate teacher preparation is successfully addressed. Although not sufficient, this is a necessary condition for effective reform. Since the type of preparation that addresses the needs of teachers is not available through the standard university science curriculum, a practical alternative is to offer special courses for teachers in science departments. The instructors in such courses must have a sound understanding of the subject matter, of the difficulties that it presents to students, and of effective instructional strategies for addressing these difficulties. It is important for science faculty to recognize that the teachers completing these courses must be prepared to teach the material at an appropriate level in K-12 classrooms. The choice of an appropriate curriculum is critical. We have found that teachers often try to implement instructional materials in their classrooms that are very similar to those they have used in their college courses. Therefore, even though it has not been our intent to have young students work directly with *Physics by Inquiry*, we have designed the curriculum so that it can be used in this way by experienced high school teachers.

Our experience indicates that it is not easy to develop good inquiry-oriented instructional materials. Therefore, unless faculty are prepared to devote a great deal of effort over an extended period to the development of a course for teachers, they should take advantage of already existing instructional materials that have been carefully designed and thoroughly tested. The development of any new curriculum should be based on research, with rigorous assessment an integral part of the process. In this way, cumulative progress at all levels of science education can become possible.

ACKNOWLEDGEMENT

The authors deeply appreciate the many contributions over the years to the teacher preparation program by all members of the Physics Education Group (past and present, resident and visiting). We recognize our debt to Arnold B. Arons for his insights into the needs of teachers and for his initiative in introducing the first course for teachers in the Department of Physics at the University of Washington. Special acknowledgment is due to the National Science Foundation for the continuing support that has enabled the group to conduct a coordinated program of research, curriculum development, and instruction and to provide an environment in which the teacher preparation program has thrived.

ENDNOTES

1. This section draws on L.C. McDermott, "A perspective on teacher preparation in physics and other sciences: The need for special science courses for teachers," *American Journal of Physics* 58, 734–42 (1990).
2. The process of research and curriculum development as implemented by the Physics Education Group is illustrated in many papers that appear in the *American Journal of Physics*. For an overview and more general discussion, see L.C. McDermott, "Millikan Lecture 1990: What we teach and what is learned—Closing the gap," *American Journal of Physics* 59, 301–315 (1991).
3. L.C. McDermott, P.S. Shaffer, and the Physics Education Group at the University of Washington, *Physics by Inquiry* (Wiley, New York, 1996), Vols. I and II. A third volume is under development.
4. L.C. McDermott, P.S. Shaffer, and the Physics Education Group at the University of Washington, *Tutorials in Introductory Physics*, Preliminary Edition (Prentice Hall, Upper Saddle River, NJ, 1998).

5. For another discussion of the need for special physics courses for teachers, see K.G. Wilson, "Introductory physics for teachers," *Physics Today* 44 (9), 71–73 (1991).
6. A.B. Arons, *The Various Language* (Oxford U.P., New York, 1977). This book was developed for the original version of the course for elementary school teachers.
7. L.C. McDermott, "Combined physics course for future elementary and secondary school teachers," *American Journal of Physics* 42, 668–676 (1974).
8. L.C. McDermott, "Improving high school physics teacher preparation," *Physics Teacher* 13, 523–529 (1975).
9. A.B. Arons, *A Guide to Introductory Physics Teaching* (Wiley, New York, 1990), pp. 3–6.
10. A selection of articles can be found in L.C. McDermott and E.F. Redish, "Resource Letter PER–1: Physics Education Research," *American Journal of Physics* 67, 755–767 (1999). Although most of the studies cited in this resource letter refer to students at the university level, similar difficulties have been identified among younger students.
11. See, for example, J. Griffith and P. Morrison, "Reflections on a decade of grade-school science," *Physics Today* 25 (6), 29–34 (1972); R. Karplus, "Physics for beginners," *Physics Today* 25 (6), 36–47 (1972); and J.W. Renner, D.G. Stafford, W.J. Coffia, D.H. Kellogg, and M.C. Weber, "An evaluation of the Science Curriculum Improvement Study," *School Science and Mathematics*, 73 (4), 291–319 (1973).
12. See, for example, K. Wosilait, P.R.L. Heron, P.S. Shaffer, and L.C. McDermott, "Development and assessment of a research-based tutorial on light and shadow," *American Journal of Physics* 66, 906–913 (1998); L.C. McDermott and P.S. Shaffer, "Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding," *American Journal of Physics* 60, 994–1003 (1992); P.S. Shaffer and L.C. McDermott, "Research as a guide for curriculum development: An example from introductory electricity, Part II: Design of instructional strategies," *American Journal of Physics* 60, 1003–1013 (1992); and M.L. Rosenquist and L.C. McDermott, "A conceptual approach to teaching kinematics," *American Journal of Physics* 55, 407–415 (1987).

13. M.B. Rowe, "Wait time and rewards as instructional variables, their influence on language, logic, and fate control: Part one—wait time," *Journal of Research in Science Teaching* 11, 81–94 (1974).
14. See the third article in Note 12.
15. *Elementary Science Study* (Educational Development Center, Newton, MA); *Science Curriculum Improvement Study* (University of California, Berkeley, CA).

Inquiry Teaching in Biology

Kathleen M. Fisher

INTRODUCTION

Many organizations have recently called for reform of science education in the United States, among them the Carnegie Commission on Science, Technology, and Government in 1991, the National Commission on Excellence in Education and the National Science Board on Precollege Education in Mathematics, Science and Technology in 1983, and in 1978 the National Science Foundation (NSF) Directorate for Science Education. In 1989, 1993, and 1998 the American Association for the Advancement of Science established standards for science learning, as did the National Research Council in 1996. Many states are in the process of establishing their own standards or have just finished doing so. At this point, a very large number of efforts are under way to improve American science teaching so as to produce both a scientifically literate public and better prepared science majors.

For example, I am currently involved in a project sponsored by the NSF that is national in scope and aims to promote college and university learning based in inquiry (Ebert-May & Hodder, 1995). Working in this project gives me an opportunity to hear what science faculty want to know about such

learning. “Is it effective?” “How do you know?” and “What is the evidence?” are understandably some of their most common questions.

These questions are hard to answer, in part because there are so many different varieties of learning based in inquiry and partly because we are building on a research foundation that has spanned a quarter of a century and involves numerous fields of study, including but not limited to cognitive science, linguistics, psychology, sociology, and science education. The evidence has grown so gradually and is now so pervasive that, to my knowledge, there isn’t a single definitive paper that sums it all up.

I have tried to organize this chapter to provide brief answers to some of the questions raised by my biology colleagues and to provide some useful references for further reading. I consider what inquiry-based learning is, why it is useful, when to avoid it, some strategies for its employment, lecturing in active learning, some features of inquiry-based and active learning, a thinking tool, learning communities, and the evidence for the feasibility of learning by inquiry.

WHAT IS INQUIRY-BASED LEARNING?

Different types of learning by inquiry include guided inquiry, open-ended inquiry, project-based learning, inquiry in collaboration with teachers, and learning by problems or cases (see McNeal & D’Avanzo, 1997 and “Some Inquiry-Based Strategies” below). The term “inquiry-based” is sometimes interpreted to mean that students are engaged in studying a phenomenon and at other times to mean they are engaged in questioning. Often both features are included in courses based in inquiry.

There is also a growing collection of strategies to bring active learning into classes large and small that were previously taught by traditional lecture methods (see Ebert-May, Brewer, & Allred, 1997 and “Lecturing with Active Learning” below). I describe my version of an active learning lecture course as well as reciprocal teaching, dyads, and jig-saws. These would fit under the broader definition of inquiry learning, but I have chosen to separate them because I tend to fix on the narrower definition of inquiry as study of a phenomenon.

WHY USE INQUIRY-BASED TEACHING?

Inquiry Mimics Everyday Learning

Consider how a child learns. A parent and toddler encounter a neighborhood dog. The toddler squeals and claps. The dog prances around, wags her tail, licks the child's hands. Soon the mother and child see another dog, and then another. Each day that they go out, the child sees a few more dogs. The dogs come in a wide variety of shapes, sizes, and colors. They may have long hair or short, long tails or short, ears that stand up or ears that hang down. But there are some constants as well: The shape of the dogs' heads, the shape of their paws, the way they bark and wag their tails, the way they move. When the toddler first begins seeing dogs, the mother often says the name: dog, puppy dog, Collie dog, big dog. Eventually the child says the names, too.

From these specific encounters with specific dogs, a child's mind automatically and subconsciously forms the general idea of dog. In the same way, a child acquires many, many other general concepts—cat, house, living room, run, walk—gradually building from specific experiences general knowledge of the world. Much of this knowledge of the world is intuitive and implicit rather than conscious and explicit. We are not very good at describing how we recognize a dog or how we distinguish a dog from a cat, even though our minds become very skilled at doing it.

There is much to be learned about how the mind automatically generates and uses general categories. But several observations about the process have strong implications for teaching and learning. Formation of categories occurs spontaneously upon exposure to multiple examples. In many learning events, experiences with specific instantiations of an idea come first; extraction of the more general idea follows, often subconsciously. And opportunities to interact with an object help learners to deepen their understanding and make finer discriminations.

Escaping the Deadly Dull

Almost any professor or teacher today will tell you that students are often absent, often uninterested, and often inclined to favor memorization over making sense. Why is that? We seldom stop to think how deadly dull higher education has become. The great God Coverage drives teachers to pack ever more facts into each lecture and to use labs as just another means of transmitting information. Multiple-choice tests reward simple low level learning: recognition

of key phrases and ideas. The student's responsibility is to accept and absorb volumes of content provided by the experts. Where is the creativity? The engagement? The challenge? The self-expression? The opportunity to pursue an interest? And where do students learn about the other half of science—the *processes* involved in creating the content they are so dutifully expected to learn?

Restoring the Balance

Among many forms of learning by inquiry are some common features. Students typically are engaged in active learning. They are expected to take a greater share of the responsibility for their own learning. Most important is that they are rewarded for higher levels of thinking. There is also greater emphasis on conveying the ways in which new knowledge is generated and old knowledge is evaluated and applied in new contexts. Inquiry learning is therefore intrinsically more interesting and rewarding for both students and teachers than our established patterns of teaching and learning.

Building Bridges Between Concrete and Abstract

Concrete ideas provide important tools for thinking (Lakoff, 1987). Through a process of metaphorical mapping, George Lakoff and Mark Johnson observed in 1980, familiar concrete experiences help us think and talk about abstract things. Love, for instance, a most abstract concept, is understood as a journey. "We're flying high." "We've taken a wrong turn." "We're spinning our wheels." "We're off track." We're not usually conscious of our cognitive mappings but our expressions give them away. The mappings are consistent across people, across time, and often across cultures.

Yet in spite of the recognized value of concrete referents, academic presentations often skip the practical and jump straight into the abstract. It is one of the many ways in which "fat is trimmed" and "corners are cut." Read about Gregor Mendel, for instance, in most introductory biology or genetics textbooks. You'll get numbers of peas, lists of traits, and important ratios. But will you learn how to grow a pea plant? How to prevent it from self-fertilizing? What is involved in crossing one pea plant with another? What each pea represents? All of these practical aspects of Mendel's work—the things he spent most of his life doing—are deemed too trivial to describe (there are some exceptions as J.H. Postlethwait and J.L. Hopson demonstrated in 1995). Yet these concrete beginnings provide the visual

images that allow us to comprehend what it means to cross two pea plants and they help us to make sense of the rest of it. Learning founded in inquiry provides motivation for us to get our feet back on the ground.

WHEN TO AVOID INQUIRY-BASED TEACHING

If you believe it is your responsibility to convey as many facts as possible to your students in the shortest possible time, then inquiry teaching is probably not for you. The lecture is a paradigm of efficiency for transfer of information. Or you may be intrigued but not quite yet ready to take the leap. I thought for several years about introducing active learning methods into my lecture course on Human Heredity before I actually took the plunge. Trying something new can be scary. Reading a pioneering paper on the topic, that of D. Ebert-May et al. in 1997, gave me both specific strategies and courage. Participating in the FIRST project sponsored by the NSF (Ebert-May & Hodder, 1995), which aims to promote inquiry learning through the use of biological field stations, pushed me over the edge. It helps when teachers experience active learning strategies themselves (in the student role) and when they acquire a handful of strategies or more for their toolbox. In that sense, perhaps the brief descriptions here and the accompanying references will be useful.

SOME INQUIRY-BASED STRATEGIES

This section provides very brief descriptions of some common strategies for teaching by inquiry.

Guided Inquiry

Guided inquiry, so termed by Ann McNeal and Charlene D'Avanzo in 1997, is also called privileging, as C.W. Keys named it in 1997. Its goal is to provide access to difficult scientific ideas. I use guided inquiry in my biology course for prospective elementary school teachers.

Before each lesson, I elicit the students' prior knowledge about the topic, usually through a class discussion. The goal is to bring to the surface their underlying assumptions. Some assumptions serve as foundations for learning, but others actually interfere with comprehension. Ponder questions—questions asking “why”—at the beginning of each lesson help in eliciting student understandings of everyday events. Students work in groups to perform activities,

such as observing osmosis or modeling mitosis, and make observations, such as how a bean grows. The activities are quite simple but they illustrate important biological phenomena and many are designed to challenge naïve conceptions. Before each activity, students predict the outcome. This is another valuable means for eliciting underlying assumptions. In order to predict an outcome, students must make sense of the activity, construct a mental model of it, and run a mental simulation. In doing so, they draw upon their assumptions and beliefs, which are often different from those of scientists. The students discuss their predictions within their groups and attempt to come to a consensus, although this is not required. Once they have made their predictions in writing, their interest in the outcome of the experiment is heightened. The student groups work through the lesson, collecting data and responding to the questions in it. Questions embedded in the lesson aim to prompt their higher order scientific thinking about the phenomenon being examined.

A very interesting and consistent outcome is that, when the consequence of an activity differs from the students' predictions, they usually assume that they did the experiment wrong. It doesn't even occur to them that their mental model might need rethinking. To persuade students to reconsider their predictions, we compare results of all student groups. If most or all groups observed the same results, the outcome is validated. At that point, students are often reluctantly willing to reconsider their expectations.

These biology lessons can be viewed and downloaded from the World Wide Web (Fisher, 1996). There have been more than forty-five thousand visitors to the Biology Lessons web site in the past two years, and the site has been mirrored in both South Africa and Hong Kong. There is some evidence that this approach succeeds in promoting higher order thinking (Christianson & Fisher, submitted; Gorodetsky & Fisher, 1996).

Open-Ended Inquiry

Open-ended inquiry engages students even earlier in the scientific process and they take on more responsibility for the lesson. The teacher creates the context and establishes the constraints within which the students work. It is up to the students to identify the question to be asked and to design an experiment to provide the answer. These are, of course, two of the most challenging and engrossing steps in the entire scientific process. Students usually start out with very general questions that the teacher helps them trim down to something testable. The teacher also provides guidance and resources. Open-ended inquiry into the

processes of decomposition by fourth graders working with an insightful teacher, Terez Waldoch, has been captured on a videotape available from Annenberg/CPB (Schnepps, 1994b). Open-ended inquiry at the university level is described in Ann McNeal and Charlene D'Avanzo's publication of 1997.

Project-Based Learning

In learning based on a project, a context is created for open-ended inquiry. Often the context is both real and current, and a news film or newspaper article may be used to describe the situation. An ecology course, for example, might draw upon a quarrel between a farming conglomerate and a group of environmentalists over a piece of land. A chemistry course might examine a conflict between townspeople and a paper plant about effluent contaminating a local stream. Whatever the situation, students are asked to identify the pertinent scientific questions and to determine what data can be collected to help resolve the dispute.

This has the advantage of showing students that science has practical application outside the classroom and can have a significant role in social and political conflicts. Such exercises can help students to learn to think objectively in emotional situations. And they often prompt original research into situations where several parties beyond the classroom are interested in the outcome. This raises the status of the students and increases the pressure on them to do a completely professional job in their research.

Like all original research, these projects are uncertain in outcome and there is potential for frustration. It may not be possible for the same groups to repeat the experiment as researchers often do in real life. When several student groups are working on the same question, the project may result in mutual validation or in magnifying confusion. One thing for sure: it is an easier situation for the teacher to manage when all groups are pursuing the same question.

Teacher-Collaborative Inquiry

Collaboration between teacher and students works best in small classes. Student groups may examine several different facets of the same problem. The problem is authentic, the research is original, and often several parties are interested in the outcome. This approach can be both satisfying and challenging. It is probably difficult at times for the teacher to treat the students as equal co-investigators, but then skillfully managed collaboration can create growing and learning situations for all participants.

Problem-Based or Case-Based Learning

Methods addressing specific cases have been used extensively for years in the professions, especially medicine, law, and business. They are not yet common in science. In these cases, students analyze existing situations rather than develop their own projects. The usual approach is to give students a real-life problem, ask them to identify the essential medical or legal or scientific or business issues, and to do the research necessary to produce a resolution. Students generally work in groups. The method lies at the intersection of the society and the discipline. Proponents find it is a way of humanizing science, bringing together scientific methodology and social values. For more information about case-based learning in science see C.F. Herreid's web site developed in 1998.

LECTURING WITH ACTIVE LEARNING

With some trepidation, this semester I changed into an active learning course my traditional lecture course in human heredity. The class meets for three fifty-minute lecture periods a week in a small room with fixed chairs and raised platforms. The room holds sixty-eight students and is filled to capacity. Human Heredity is a general education course for students not majoring in biology and so is relatively easy to modify.

On the first day I introduced students to the format of the course using a colorful poster to display our intended schedule for each fifty-minute period. I subsequently modified the schedule slightly:

- 11:00 – 11:10 Small Group Discussion
- 11:10 – 11:20 Class Discussion
- 11:20 – 11:35 Presentation
- 11:35 – 11:45 Quiz
- 11:45 – 11:50 Journal

We are working through a chapter a week in a human heredity text and students turn in assigned problems weekly. I encouraged the students to move around and form new groups daily for the first week, and at the fourth class meeting we formed fixed groups of three or four students. We are three weeks into the semester and so far, my students and I are very happy with the situation. It is fun! I follow the schedule loosely rather than rigorously, extending the presentation or the discussion when it seems useful. I generally use the discussion time for eliciting prior knowledge and the subsequent class discussions to build bridges from

students' prior knowledge to the material to be presented. The quiz—at least one a week—centers on material from the previous class meeting, sometimes taken by individual students and sometimes by groups. Students have developed an ease and willingness to speak out in the large class discussions, which is very refreshing. Interactive lecture classes use little of the study of phenomena that is one component of learning by inquiry.

This approach gives me an entirely new way of thinking about the content. Instead of trying to cover everything in each chapter in reasonable detail, I think about what the students most need to know to function well in society, what they are already likely to know, and what I know about their naïve conceptions. This leads me to be quite selective and discriminating in my choice of topics. It is clear that students will be exposed to fewer topics, but I believe they are more likely to comprehend and remember them.

The students report that they like the group work best of all. They are less fearful of learning science and actually enjoy coming to class. Their attendance, which remains very high, verify this. Some initially worried about what the Right Answer is, but I turn that around and say, "If you have any questions please, please ask them" or, "Please feel free to consult your book for the correct answers." They have a much greater responsibility for their own learning and for determining what are believed to be the right answers.

Reciprocal Teaching

Anne Marie Palinscar and Ann Brown, as they report in an article published in 1984, introduced reciprocal teaching into the middle schools of a large school system. The process aims to foster monitoring and fostering of comprehension. It produces active rather than passive reading. The two were working with students reading science texts. In small groups with an assistant or aid, the students read one paragraph at a time and then summarize what it said, identify a question it raises, identify a point in the paragraph that needs clarification, and then predict what is likely to be in the next paragraph. The impressive thing about this active reading method is that the researchers began with the poorest twenty percent of the readers in each class, yet at the end of six months the participants were the best readers. This is the most effective educational intervention I have ever seen and you would think it would be in every school system in American by now—but it isn't.

Dyads

In a lecture course, it can help to stop after describing a difficult topic and ask students to discuss the material with a neighbor, to determine what makes sense to them and what their questions are. Tell the students they will have to stop talking when you send the signal, which will be in X minutes. A bell or chime can then restore order very quickly. The student pairs can then ask their questions and get the clarifications they need for comprehension. Or they can write a one-minute paper about the muddiest point, and you can address their comments in the next class. You can learn something about what erroneous assumptions you are making with respect to students' background knowledge and how to improve your presentation next time. Some people use this approach even with very large lecture classes.

Jig Saws

A jig saw is generally a variation on group work. For simplicity, let's suppose there are four groups of four students apiece. Each group may concentrate on obtaining information about a different topic, possibly through laboratory observations or literature review. When the students feel they have mastered their topic, new groups are formed, each containing a student from each of the four previous groups. Every student is then responsible for teaching the other three in the group about the topic the student has previously worked on.

SOME IMPORTANT FEATURES OF INQUIRY-BASED AND ACTIVE LEARNING

Eliciting Prior Knowledge

Eliciting prior knowledge can reveal solid starting points for a new lesson, critical gaps in the students' knowledge, misunderstandings, and important alternative conceptions. An *alternative conception* (a term with many synonyms, including *misconception* and *naïve conception*—I will use these three terms interchangeably) is an idea held by a learner that differs significantly from the scientific conception. A misconception is an error or misunderstanding to which the learner has a strong commitment. Naïve conceptions are *persistent*, well embedded in an individual's cognitive ecology, and difficult to correct, especially by

didactic methods. Misconceptions are also widely shared, often by from twenty to sixty percent of students in a given class. For a compendium of misconceptions that have been studied see the articles by J.H. Wandersee, J.J. Mintzes, and J.D. Novak along with that by H. Pfundt and R. Duit, both published in 1994.

It is astounding, for example, how few students actually understand the basic idea of photosynthesis even though the topic tends to be “covered” in middle school, in high school, and again in college. The misconception that completely blocks comprehension appears to be that gas has no weight. If gas has no weight, then how could carbon dioxide be used to construct trees? Students dutifully memorize the formula for photosynthesis but look for more logical explanations: “The weight of a tree comes from the soil, the nutrients, the water,” according to M. Schnepf and the Science Media Group in a video of 1994. The same misconception probably contributes to the belief that the bubbles in boiling water consist of hydrogen and oxygen for unlike water vapor, which many students think is visible and only temporarily present in air, these are known gases that also are assumed to have no weight.

Instructors in most lecture courses today have little knowledge about what their students are thinking. Without free discussion, without an awareness of some of the most persistent misconceptions that researchers have discovered, without any existing feedback mechanisms other than multiple-choice tests in which the instructor sets the questions, the answers, and the distractors, the disjunction between what students “know” and what teachers “know” grows ever wider.

Prediction

Dr. Roger Christianson, Chair of the Biology Department at the University of Oregon, notes that engaging students in making predictions is probably the single biggest difference between inquiry and standard biology labs. Predicting requires students to construct a mental model of an event, run a simulation, and commit themselves to an anticipated outcome. Like betting on a race, prediction heightens their interest in observing the actual outcome. Videotapes of student groups demonstrate that the most interesting discussions occur when students are making predictions and again when they are comparing their predictions with their results. Prediction and the resolution of differences between predictions and observations is the heart of the learning process in these labs, the place where conceptual change is most likely to occur. Among facets of inquiry teaching I would put prediction and explanation on the absolutely essential list.

When observations differ from predictions, students typically make the assumption that they must have done the experiment wrong. It doesn't occur to them to question their assumptions. It usually isn't until they see that all or nearly all the groups observed the same outcome that they begin to question their mental model and predictions. Many teachers deliberately use anomalous, unexpected events to challenge known misconceptions and to help students see in a new way.

Engagement with a Phenomenon

Each lesson here has students observe a phenomenon, event or simulation that illustrates the scientific principle being studied. The activity draws them into the problem, generating interest and motivation. It also provides the platform for making predictions. Guided interaction with the phenomenon gives students an opportunity to understand it better. It also serves as an anchor in memory for the related abstract ideas, since we tend to remember concrete experiences more easily than other kinds of knowledge. If the activity has been designed to challenge a misconception, the surprise associated with the outcome can increase its memorability.

One problem in biology is that so many events are invisible to the naked eye. We can't observe respiration or photosynthesis. But if we seal a plant in soil in a bottle for a semester and see that it survives so long as it gets plenty of light, we may be a little more convinced that plants both respire and photosynthesize. (Many students believe that photosynthesis is respiration in plants, or that animals respire while plants photosynthesize.) They seem to be able to imagine that in this situation, respiration produces enough carbon dioxide to support photosynthesis, and photosynthesis produces enough oxygen to support respiration. If Americans are ever to understand the issues of global warming, they need to grasp some of these basic ideas.

Group Work

When young children are learning a new skill, you often see them talking out loud but to themselves. Adults do the same thing but they tend to do their self-talk silently. Since talking is vital to understanding, students need to find their voice in the classroom. Through conversation, students gradually move from perceptual knowledge founded in images and other sensations to conceptual knowledge, based in the words that are inseparable from thought. This transition is the key to learning an academic subject such as biology.

Peer evaluations are useful for monitoring progress and evaluating each individual's contribution. In my class, students evaluate themselves as well as others in their group. The consensus on who contributed what is usually typically very high. This allows me to give a grade on a group project and adjust it up or down for individual students.

Higher Order Thinking

One of the teacher's roles is to prompt students to seize on central issues and think about deeper levels of interpretation (Resnick, 1983, 1987). In studying boiling water, for example, it is always useful to ask questions such as: Why do the bubbles form at the bottom of the container? (It is closest to the heat source.) What is in the bubbles? (On average, perhaps one student in the whole class will know the answer is water vapor; most think the bubbles contain hydrogen and oxygen.) Why do the bubbles rise to the top? (Most will know it goes into the air.) How does it change? (Most do not understand that the water molecule remains intact and simply separates from other water molecules.) In general, questions that are so basic that they are almost never asked in standard science classes provoke the greatest amount of rethinking on the part of the students.

It takes time and patience to ask the students to think about questions such as these and to guide their discussions toward appropriate answers. At the same time, the pressure to move on leads to the constant temptation to slip into teaching by telling. It is OK, even desirable and necessary, to slip into the telling mode sometimes. The important thing is to keep raising good questions. To sail through a lesson without asking deep questions is as serious an oversight as failing to prompt students to make predictions and generate explanations.

A good rule of thumb is that students spend at least as much time making sense of a lesson as they do in performing an experiment or activity, and often more. This is where the science illustrated by the activity is developed or lost. Reflection occurs as students talk to their peers within their groups, in the class discussions before and after lessons, as student groups work together to represent their knowledge with a thinking tool, which I'll describe shortly, and in the assessments.

In an inquiry class, assessment is an ongoing process. A teacher can learn a lot from the level of engagement and understanding of each student during the class discussions, by talking with student groups individually, and by listening in on conversations. It also helps to ask students to give presentations, write essays, search the web for related information, and perform other skills of a higher order.

Frequent opportunities for assessment and feedback are preferred. The important thing in testing is that it is not business as usual. Multiple-choice tests are not the preferred method. A teacher needs to concentrate on higher order thinking skills: synthesis, analysis, evaluation, application, performance.

Student-Centered Classes

For a teacher to share with students the responsibility for learning means an important shift of power. Students turn from recipients to actors. They ask questions that teachers had never before thought to answer. They bring in learning from other classes, from the TV and other media, and from their parents, and try to fit it all together.

Such an enterprise can seem like risk-taking for a teacher, in part because it is impossible to know all the answers when students are asking the questions. But the important thing to realize is that it is OK not to know all the answers. The teacher can prompt students to seek answers to their questions and share them with the class. The camaraderie and respect that grows between teacher and students in a class centered in students is a wonderful reward.

A THINKING TOOL TO SUPPORT CONSTRUCTION OF KNOWLEDGE

Many different tools are available to help us record our knowledge, analyze it, organize it, understand it, see it in new ways, and share it with others. Using such tools can make us smarter, more capable learners and thinkers. We are able to do things with such tools that we couldn't accomplish as easily or at all with our minds alone. This phenomenon has been described as distributed intelligence (Saloman, 1993; Pea, 1985; Pea & Gomez, 1992).

I will describe one such tool here: a thinking and knowledge analysis tool, the SemNet[®] software (Fisher et al., 1990; Fisher, 1991; Fisher & Kibby, 1996; Fisher, Wandersee, & Moody, in press). SemNet[®], which has been used by third graders up through graduate students as well as by professionals, is an application for Macintosh computers that can create a map of ideas having many complex interconnections. It can serve as a tangible representation of the user's thinking that then supports the user's reflection, revision, and polishing of ideas. SemNet[®] provides a space in which groups of students can think together about their experiences and how to make sense of them. It provides a forum for interpretation and negotiation of ideas.

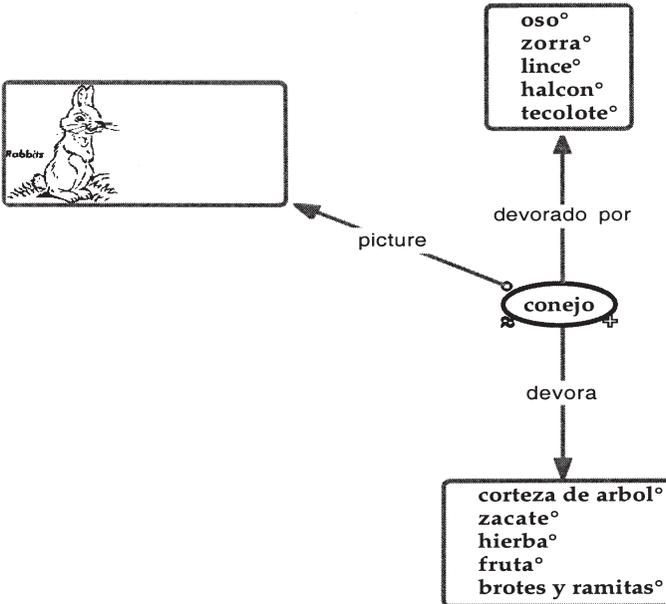
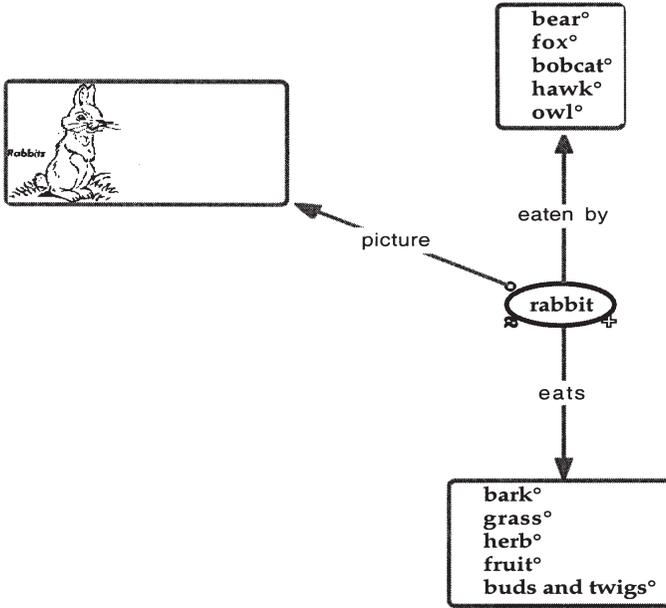
The *process* of constructing knowledge (net-building, mapping) generates much thought and discussion among students. This is where the major pay-off occurs (see, for example, Christianson & Fisher, submitted; Gorodetsky & Fisher, 1996). Students who construct semantic networks spend a lot more time on task thinking about biology than students who don't. The product (the semantic network) is also useful as a reference, a resource, and a record of what was thought in a given context at a given point in time.

Among many things that studying semantic networks constructed by students, teachers, and scientists has taught about how people think is that while there is no constrained set of relations that is useful for representing all biology knowledge, just three relations are used half the time. There is no consensus on the particular words used to describe the relations—people describe them in different ways (some alternatives are shown below), but the meaning remains similar. They are:

- ▶ Has part / is a part of (has component, contains)
- ▶ Has type / is a type of (has example, has class, set has member)
- ▶ Has characteristic / is a characteristic of (has attribute, has trait)

We have also become aware that students for whom English is a second language (ESL) have greater difficulty understanding the relations in biology than the concepts. Most relations are verb phrases, and these little words are simply more difficult to master than nouns, in part because their meanings vary with the context. This follows the pattern seen as children learn their first language: nouns before verbs. Being able to help ESL students to master essential relations is a significant benefit of using SemNet[®], since the relations are used over and over again throughout biology. Figure 1 shows the corresponding frames of an English/Spanish SemNet[®]. SemNet[®] simplified the representation of complexly interlinked, ill-structured knowledge by showing one central concept at a time with all of its links to related concepts. Seeing words embedded within robust descriptions may be helpful to new second language learners, especially when the representations are accompanied by pictures.

FIGURE 1. ENGLISH/SPANISH REPRESENTATION OF THE CENTRAL CONCEPT, CONEJO (RABBIT), IN A FOOD WEB NET



NESTED LEARNING COMMUNITIES

Lauren Resnick, a cognitive psychologist at the University of Pittsburgh and founding director of the Institute for Learning Research, has been working with several entire school systems to develop a new theory of school organization, everybody up and down the hierarchy of the school system is responsible for learning. Participants are responsible for continuous learning themselves, and for promoting learning of those in their care (that is, those below them in the hierarchy). This is an exciting vision, and we are delighted that Dr. Resnick is now working with the San Diego City Schools and is involved in the creation of a San Diego Institute for Learning Research.

WHAT IS THE EVIDENCE?

Motivation for finding more effective teaching and learning strategies in science began about 1980, when it was becoming strikingly clear that the American public is largely illiterate in science (Fisher & Lipson, 1980; National Science Board, 1983; National Commission on Excellence in Education, 1983). A scientifically and technologically advanced country with a scientifically illiterate public is at a serious disadvantage in the world. To this day, many of our decision makers in Washington, D.C. and in the states lack more than the most rudimentary understanding of the issues. The evidence for the need for change in the ways we teach and learn, as well as for the benefits of change, is so extensive that I can only pick a few examples to cite here.

Among the most interesting and persuasive comparative studies are those that A. Van Heuvelen published in 1991. He examined many dozens of physics courses being taught by high school and college teachers across the country. He found that students in courses using active instructional strategies based in cases or other research significantly and consistently outperformed students in traditional courses. D. Hestenes and I. Halloun, publishing in 1995, have developed the force concept inventory, a test being used by physics teachers across the country to determine how well their students are understanding mechanics. The general finding is that in traditional lecture courses, student understanding does not go very deep.

Another interesting comparative study comes from William Schmidt and the International Education Association's Third International Mathematics and Science Study (TIMSS, 1998; Schmidt, McKnight, & Raizen, 1996). It shows that while the United States has improved in some areas during the past twenty

years, it is still far from being a top-performing country. Even more interesting are the comparisons among curricula. In top performing countries such as Japan and what was West Germany, a small number of science topics is taught each year and each topic is taught only once throughout the student's career. In contrast, in the American curriculum, sixty-five topics or so are taught a year per science course. And each topic is repeated again and again throughout the curriculum. Schmidt describes our curriculum as a mile wide and an inch deep. In other countries science books are small and focused, not intimidating. Students can carry the books in their pockets and know they are responsible for everything in them. In the United States, science books are like encyclopedias—too heavy to carry to school, too overwhelming to take seriously, too superficial to make a lot of sense, and so full of topics that any given teacher can only “cover” a fraction of them.

In 1983 and 1987 Lauren Resnick published interesting reviews that provide a cognitive science perspective on the evidence to support higher order thinking. Anna Sfard (in preparation) offers a review from the mathematics education perspective on the benefits of constructivist teaching. J.L. Lemke, whose study came out in 1993, as well as E.H. van Zee and J. Minstrell published in 1997, are among the researchers who are looking at the impact of language and reflective discourse on science learning. There are many wonderful qualitative studies on the benefits of the new teaching strategies such as that published by R. Driver, H. Asoko, J. Leach, E. Mortimer, and P. Scott in 1994; Driver, A. Squires, P. Rushworth, and V. Wood-Robinson the same year; J.R. Baird and I.J. Mitchell in 1986; and D. Brown and J. Clement in 1989. This is only a sliver of the research supporting the reform movement, but should be enough to get an interested reader started.

The evidence, in sum, is compelling both for the need and for the benefits of change in the ways we teach and learn science in the United States. Introducing significant change into our mammoth educational system is a major challenge that has engaged many branches of the government for the last quarter century. Inertia is the biggest problem, coupled with major pockets of resistance such as the conservative movement in California. We are still searching for an ideal instructional method that fits within the budget we are willing and able to allocate for education. In the meantime, an array of methods based in inquiry is being implemented and tested, and this seems like the most promising approach. So long as we remain focused on the effective features of instruction by inquiry such as *eliciting prior knowledge, prediction, engagement with a phenomenon, group work, higher order thinking and classes centered in students*, I believe, we will remain on the right track. To the extent that we are able to reorganize our

classrooms, school systems, and textbooks to emphasize higher order learning, and we are able to effectively use computers and other tools to help our learners think smarter, we will succeed in advancing science learning.

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