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ABSTRACT

This paper elaborates upon the idea of pedagogical content knowledge through close examination of a teacher's learning in science and addresses a question derived from Shulman's (1986) original work on teacher knowledge: "What is learning for teaching?" Pedagogical knowing is viewed as the practice of seeing into the subject matter through the eyes, hearts, and minds of learners, an image adapted from Ball. Presented is a case study of a second year, fifth-grade teacher as she conducted an investigation of aquatic ecology over a period of several months, in the context of a four-year project in which teachers examined science, science learning, and teaching through their own and their students' experience as learners. How this teacher came to learn to see into the subject matter, her own learning, and her students' learning as she worked to understand aspects of the ecology of a local pond, and how her experience figured into her identity as a learner and her practice as a teacher are analyzed. (Author/WRM)

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From Knowledge to Knowing: An Inquiry into Teacher Learning in Science[1]

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In this paper we elaborate the idea of pedagogical content knowledge through close examination of a teacher's learning in science. We address a question derived from Shulman's (1986) original work on teacher knowledge: What is learning for teaching? We locate our exploration in a view of pedagogical knowing as a practice of seeing into the subject matter through the eyes, hearts, and minds of learners, an image we adapt from Ball (in press). We present a case study of a second year, fifth grade teacher as she conducted an investigation of aquatic ecology over a period of several months, in the context of a four-year project in which teachers examined science, science learning, and teaching through their own and their students' experience as learners. We analyze how this teacher came to see into the subject matter, her own learning, and her students' learning as she worked to understand aspects of the ecology of a local pond, and how her experience figured in her identity as a learner and her practice as a teacher.

That good teaching, whatever else it may entail, rests on a foundation of knowledge in and about a discipline has become an indisputable tenet of current educational reform. This is in important part due to Shulman (1986, 1987) and his colleagues (Wilson, Shulman, and Richert, 1987), who more than a decade ago launched a vigorous program of research to address what Shulman called the "missing paradigm" problem, that is, the omission of subject matter knowledge from research on the study of teaching. The then prevalent paradigms of research on teaching, Shulman argued, neglected to ask "how subject matter was transformed from the knowledge of the teacher into the content of instruction. Nor did they ask how particular formulations of that content related to what students came to know or misconstrue (even though that question had become the central query of cognitive research on learning)" (Shulman, 1986, p. 6).

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The "cognitive turn" in research on teaching that Shulman inspired marked a theoretical shift in the study of teaching. It gave rise to a new set of questions focused on the sources and organization of teacher knowledge—how it is acquired, represented, and then re-represented in teaching—as well as questions about how learning *for* teaching occurs (Shulman, 1986). It also gave rise to a rich program of research into the growth and forms of teacher knowledge (Grossman, Wilson, and Shulman, 1989; Wilson et al., 1987).

The questions that framed this new research paradigm on teaching were firmly grounded in a cognitivist framework. They focused on specifying the forms and categories of knowledge represented in the minds of teachers and on identifying promising modes of acquiring such knowledge. Thus the central questions of this new paradigm were organized around certain assumptions about the nature of knowledge and knowing in teaching, chiefly, of the teacher as an active problem-solving agent, whose expertise is richly contained in structured mental representations. This expertise was broadly defined by Shulman (1987, p. 4) to include "a codified or codifiable aggregation of knowledge, skill understanding, and technology, of ethics and disposition, of collective responsibility," and its sources span scholarship in academic disciplines; the materials and practices of educational institutions; research on schooling, learning, teaching, and related areas; and the wisdom of practice.

A little more than a decade later, this research paradigm continues to thrive. And, like any productive line of inquiry, it has helped pave the way for significant new approaches to research on teaching. Notable among these is the work of such researcher-teachers as Deborah Ball (in press, 1993), who, through explorations of what she views as problematical events in her own teaching of mathematics, opens up for her own and others' constructive scrutiny the often taken for granted codifications of teachers' knowledge about children, mathematics, and teaching. Her work is typified by a deep sense of the complexity emergent in actual situations of practice, complexity that is rooted in her appreciation of the creative but nonetheless tension-filled dynamic at the core of her mathematics teaching, between students' ideas and ways of knowing and those of mathematics.

In a recent paper, Ball (in press) discussed dilemmas she experienced in her everyday, moment-to-moment classroom practice in mathematics. She described her efforts to cope with them as she tried to make sense of children's ideas "across a gulf of human experience and meaning" (p. 23). It is worth noting, as we think the example below will make clear, that Ball's uncertainty in the face of classroom dilemmas was embedded in rich understanding of her students, mathematics, and teaching; it indexes a space within her practice in which what she knows is significantly problematized by her students' sense-making.

One instance Ball (in press) recounts involved a child, Ofala, who used words, drawings, and gestures integrally to explain what she thought an odd number was. In trying to make sense of Ofala's work at the time, Ball understood Ofala to be defining odd numbers in a way close to the algebraic definition, the standard idea toward which Ball was helping her students work. Upon considered study of this episode with others, however, Ball came to realize that Ofala was making a distinction between two ways of construing what the mathematical property of oddness means. This distinction, which Ball characterized as one involving the standard algebraic one and another more geometric one, has, in fact, great mathematical significance. But at the time, Ball tells us, she "completely missed the power of [Ofala's] linear arrangement" (p. 28): Among other things, Ofala's gestures were not easily "read" by Ball, and Ball herself was unfamiliar with the mathematical distinction Ofala was suggesting. In the end, Ball was left with more questions than answers—did Ofala intend to communicate two perspectives on oddness? Did Ball's own efforts to revoice Ofala's contribution lend stability to her ideas, or did it obscure her thinking? How did Ball's goals for her students' mathematical understanding shape what she heard them say?— and, importantly, with a new appreciation for ways of seeing into the subject matter of odd numbers through the words, drawings and gestures of a student. Pondering still another example of complexity from her practice, Ball wrote:

> Lots of questions; few clear or definite answers. Perhaps this is why teachers may avoid delving deeply into questions of what students know. The questions seem to multiply exponentially. And, given the fleeting and intangible nature of knowledge, no answer seems satisfying. To assume that there is a "true" picture of a child's understanding is to blot from consideration the many elements that contribute to understanding being more fragile than is convenient to assume. We would like to think that understanding can be a state or a destination, that we can observe and certify. That it is so sensitive to context, to social relations, to time and tiny filigrees of consideration, is to admit of an uncertainty in the very core of teaching and learning, one understandably unappealing for either teachers or researchers to acknowledge (Ball, in press, p. 35).

Part of the power of Ball's account lies in the sense of ongoing, intellectually honest struggle that attends her efforts to bring children's ideas and practices into productive contact with those of mathematics. A striking feature of her experience, exemplified in the Ofala episode, is that her insights into her practice are thoroughly embedded in the mathematical, discursive, material, social, cultural, and biographical particulars of the instructional situations in which she finds herself. In Ball's experience, neither student, teacher, curriculum, nor mathematics is static or ready-made (Dewey, 1902/1990). Indeed, how these come into thorny contact in particular instances of teaching mathematics may be said to define Ball's stance of inquiry toward her practice. Dilemmas, struggles, and uncertainty pervade her accounts. Articulated dilemmas are never fully resolved, that is, in some ultimate, fixed sense. More frequently, they give rise to additional questions and new perspectives, as exemplified in the case of Ofala, in which Ball's sense of her students' understandings and of the subject matter of mathematics itself were both expanded.

Ball's accounts of her "active coping" (Dewey, 1929/1990) with uncertainty represent to us yet another turn in research on teaching—one that, even as it shifts emphasis, extends the core intention of Shulman's paradigm to elaborate what it means to teach. Thus, Ball's emphasis on uncertainty in the practice of teaching (discussed also by Lampert, 1985), of matters unresolved but intelligently managed,[2] of understanding continually being constructed, shifts the emphasis from conceptualizing teacher knowledge as knowledge represented in an individual mind toward a view of pedagogical knowing as a lived, socially and historically situated, contingent, tension-filled *practice* (Lave and Wenger, 1991). As Ball herself writes, in reference to the powerful idea of pedagogical content knowledge introduced by Shulman and his colleagues (1986, 1987) to capture the various ways of formulating and representing subject matter knowledge for learners, instances from her own teaching ". . . reveal not only the temporality of practice, and its fleetingness, but also the remarkable density of intellectual and personal demands from moment to moment" (Ball, in press, p. 20). "(F)iguring out powerful and effective ways to represent particular ideas implies, in balanced measure, serious attention to both the mathematics and the children This is more easily said than done" (Ball, 1993, p. 6).

In these reflective cautions, Ball draws our attention to the ways in which every course of action in a classroom depends in essential ways on its material, social, historical, cultural, and other circumstances. She implies, here and elsewhere, some skepticism toward any view of teacher knowledge that would abstract pedagogical action away from its circumstances and represent it as the execution of a rational plan or the use of firmly codified knowledge, whether knowledge about children, teaching, or mathematics itself:

> . . . (T)eachers must do more than *use* knowledge of students. They must, on an ongoing basis, *construct* new knowledge of their students (Ball, in press, p. 9).

In this paper, we explore from yet another angle (that of a teacher's learning in science) this elaboration of teacher knowledge as, in a paraphrase of Ball (in press), ways of seeing into the subject matter, through the eyes, hearts, and minds of learners. In the case we present, learning was not explicitly concerned with acquiring new methods of teaching or amplifying a teacher's storehouse of scientific knowledge. Rather, it was explicitly approached as an opportunity for teachers to bring into focus new ways of seeing into science and science learning and teaching through their own experience as learners in a professional development setting as well as in their classrooms.

We thus tackle an issue Shulman (1986) flagged as strategic in the new paradigm of teacher knowledge studies: How does learning *for* teaching occur? We ask, What *is* learning for teaching, and how does it articulate with learning the subject matter of science and with teaching science? We locate our exploration of these questions in the view of pedagogical knowing that researchers like Ball are elaborating, that is, as a lived, socially and historically situated, contingent practice. By the term "practice," we mean to emphasize teaching as embedded in—giving shape to and being shaped by—a local culture, "a form of life, a 'world' of involvements" (Taylor, 1995, p. 62), and the teacher as an embodied agent, "a being who acts in and on the world" (Taylor, 1995, p. 176).[3]

Specifically, we examine through a case study the experience of one teacher who, as part of a professional development project, engaged in doing science. We examine the ways in which she and her colleagues took up the heterogeneous resources—texts, models, measurement devices, inscriptions, and field sites—of aquatic ecology; how she and they coped with the lack of transparency of these resources; how she managed her learning in the face of her goals, her questions, and the troubles she encountered; how she came to view her own learning in relation to her students' learning and her teaching; and how she and her colleagues positioned themselves in relation to scientific practice. We document, in short, how this teacher came to see into the subject matter of ecology, her own learning, and her students' learning, as she struggled to understand the "health" of a local pond, and how her experience figured in her identity as a learner and her practice as a teacher.

Structure of the Case Study

The case study is two-tiered, with the two tiers interleaved. The first tier consists of a running account of the teachers' experience investigating dissolved oxygen levels in a local pond, known as Alewife Pond. This takes the form of a narrative, presented as a series of four episodes Each episode is anchored in a transcript and a summary of events leading up to, included in, and following the transcribed activity. The second tier consists of our analysis of the transcribed talk and activity.

In what follows, we first briefly review our data sources and methods. Next we sketch the character of the professional development setting in which the Alewife Pond Study took place and provide an overview of the Alewife Pond Study itself. We then enter the heart of the case study. In a postscript to the case study, we examine two final episodes, one from the pond study and one from the focal teacher's classroom experience, in terms of what each illuminates about how the teacher's experience in the pond study figured in her life as a learner and teacher. We conclude the paper with some final reflections on what we see as the significance of the study.

Data Sources and Methods

The data are of two kinds. First, there are videotapes and transcripts of discussions involving the focal teacher and her colleagues as they investigated the pond. These discussions took place in the context of a professional development seminar, which during the school year met biweekly after school for two hours and during the summer for two consecutive weeks. Tables and graphs of the teachers' data, as well as texts and other authoritative sources, were often of focal interest in these discussions. Secondly, there are videotapes and transcripts of a classroom discussion from the focal teacher's class, and from an interview with project staff a year later in which she reflected on the significance this discussion had assumed for her.

From the many hours of videotape that form the documentary record of the Alewife Pond Study, we have selected episodes that represent the full range of the teachers' activities, namely, their work to understand particular measurements, to make sense of expert accounts, to use devices reliably, to interpret graphs, to argue claims, and to summarize findings. The episodes that comprise the case study serve two purposes: they mark important events in the focal teacher's experience and they exemplify the intense interplay among her activity, the world of the pond, and the discipline, discourse, and tools of ecological theory and practice.

The analysis derives methodologically from studies of human interaction that are concerned with following the activity of practitioners where and as they actually work, whether the setting is a classroom, a laboratory, a seminar room, a research vessel, a technological workplace, or an archaeological site (Goodwin, 1993, 1994, 1995; Hall, Torralba, and John, 1998; Hutchins, 1995; Latour and Woolgar, 1986; Lynch, 1991; Ochs, Gonzales, and Jacoby, 1996; Suchman, 1987). We are thus concerned with examining learning as participation in a heterogeneous, socially constituted world of relevant activity (Lave and Wenger, 1991; Rogoff, 1990), rather than as the acquisition and use of mental representations and processes by a monologic subject. We are as much concerned with what is said and done as with how; with whom; with what particular instruments, texts, and other heterogeneous resources participants use to accomplish specific activities; and with developing a sense of the participants' trajectories of participation within particular activities and practices.

The Professional Development Setting

The case study grows out of a four-year professional development research project (Rosebery and Warren, 1997, 1998), *Video Case Studies in Scientific Sense-Making*, in which educational researchers, scientists, and teachers explored science learning and teaching through various perspectives: our collective experiences doing science, the teachers' classroom practice, and their own classroom-based inquiry into their students' learning. The project had both research and development goals; through collaborative inquiry with teachers into science and student learning we sought to (a) deepen our understanding of science as a sense-making activity, (b) explore the implications of such a view for teacher professional development, and (c) document aspects of our work together in a series of video case studies (Rosebery and Warren, 1997). This project has since developed into a larger effort to understand how teacher research communities function as sites of learning, of which this paper is a part (see also Ballenger, 1998; Rosebery and Puttick, in press; Warren and Rosebery, 1995; Warren and Rosebery, 1998).

Over four years, project participants waded into ponds to investigate aquatic ecosystems, floated helium balloons to explore equilibrium, built and raced toy cars to study motion, and submerged and floated various objects to investigate buoyancy (Bodwell, 1998a; Dennis, 1998; Ogonowski, 1998; Puttick, 1998). They investigated their own questions about these scientific phenomena; designed observational and experimental studies; collected, represented, and interpreted data; constructed evidence; argued claims; and explored theories. As part of their own inquiries into classroom teaching and learning, they watched and discussed many hours of classroom videotape to explore their students' understanding in science, for example, how students made sense of floating clay boats, rust, bees, the seasons, and plant growth (DiSchino, 1998; Hanlon, 1998; Peterson, 1998). The teachers shared various forms of classroom data with one another: videotapes and transcripts of student talk and activity, student journals, portfolio assessments, and curricular experiments. These data served as the focus of ongoing conversations in which the teachers' analyses of student talk and activity in science reflexively opened up questions about their own understanding of the phenomena under study, as well as questions about the relationship of their students' sense-making to the discipline and discourse of science (Ballenger, 1998; Bodwell, 1998b; Ogonowski, 1998; Rosebery, 1998; Warren, 1998).

In this paper, we focus on the experience of Valerie Raunig Finnerty, a fourth and fifth grade teacher in a dedicated special education urban public school. Valerie entered the project with some background in science, having received an undergraduate degree in natural resources, and with one year of special education teaching experience. In her application to the project, she wrote of her childhood love of nature, her self-directed studies of animals, and her desire to convey a similar enthusiasm to her students.

During discussions about pedagogy early in the project, Valerie expressed her belief in the importance of providing students with factual, textbook-based knowledge and encouraging them to pursue their own scientific questions. These two goals were in some tension for her. She worried about how to respond to students' "tangents," wondering how tangential they really were, and whether teacher-directed science based in textbooks might not inhibit independent inquiry. At the same time, she doubted the efficacy of inquiry in providing her students with access to the "scientific canon," given its scope and detail. These were some of Valerie's expressed concerns as she undertook the pond investigation. We include them as a way of situating Valerie's scientific work in relation to her early pedagogical concerns, admittedly only a short-hand way of communicating something about her experiences with science in and out of the classroom, leading in to her participation in the project.

Overview of the Alewife Pond Study

For several months in the fall and early winter of 1991–92, the first year of the project, teachers and staff explored various aspects of aquatic ecology at three local bodies of water: Alewife Pond, Middlesex Fells (a stream), and Little River. Out of these explorations came a small set of shared interests. From the start, questions about the "health" of the sites were prominent for the teachers. Beginning in January 1992, Valerie and three other participants began an intensive investigation into water quality at the sites. Valerie and Brad Harding, a middle school science teacher, specifically mentioned an interest in understanding how the water at the sites compared, given the different kinds and quantities of aquatic life they had found in each.

The teachers were responsible for charting their own course of investigation. Project staff were available and involved, as a resource to the teachers' ongoing inquiries. Occasionally, staff would convene the whole group to share data and problems, or to refocus the groups' questions and identify potential synergies. But by and large the teachers worked under their own steam, following their own intuitions and interests in a resource-rich environment. In addition to project staff, which included a biologist trained in chemical ecology, a former chemist, and science educators, the teachers had ready access to the varied experience of their colleagues; various kinds of equipment (measurement devices, chemicals, sampling apparatus, etc.); field manuals, including one on monitoring water quality designed specifically for high school students (Mitchell and Stapp, 1991); academic and trade texts on aquatic ecology; laboratory facilities; various local bodies of water; and more.

On 2/10/92, the group sat down for the first time to consider various water quality measurements Valerie had taken on samples from the three sites. These and later measurements remained a focus of their work throughout the investigation. In the process of working to achieve a correspondence between the measurements (e.g., numerical indicators of the pond's water quality) and the measured phenomenon (e.g., the water quality or "health" of the river, stream, and pond), Valerie and her colleagues came into thorny contact with a number of diverse but related kinds of resources that are just as often found in classrooms as in laboratories: measurement devices, data produced by such devices, field observations, theories and models, manuals, and textbooks. Our analysis focuses on displaying how these resources and the teachers' relation to them became increasingly complicated as the teachers worked to construct a correspondence between water quality measurements and specific bodies of water. How Valerie and her colleagues managed and made sense of the troubles that emerged from their encounters with these heterogeneous resources, and how they positioned themselves in relation to the world of science, the world of school, and the world of their own learning, is in many ways the heart of their experience and our analysis.

Case Study

Episode 1: "These are called anomalies." (2/10/92)

Prior to this meeting, Valerie had run one test each of pH, dissolved oxygen (DO), and fecal coliform on samples from each of the three sites.[4] She, Brad, Josiane Hudicourt Barnes, a Haitian bilingual teacher who was on a one-year leave from teaching to work on the project, and Meg Wilder Watson, a fourth grade teacher and staff developer, considered the measurements

Valerie had taken at the sites: single readings of pH, DO, and fecal coliform. Each teacher in his or her own way expressed some insecurity about the reliability of the measurements, especially the DO but also the pH readings. Their sense of insecurity was understandable, given their limited experience with the measurement devices and techniques. In the following segment, the group tried to reconcile the readings with one another, with expected correspondences, and with the conditions they had observed at the pond, which included an abandoned shopping cart, submerged car tires, and a foul "gassy" odor. These observations had led to them to believe that the pond was "polluted."

1. Josiane: I-I- but you know, the fecal coliform I don't find that strange either because there's probably not that much wildlife near that pond even though we've seen deer droppings and um a rabbit. We saw a rabbit there in the fall. At- next to the river, the Little River. //And]

2. Valerie: //The pond] had a lot more than the river, at least according to these tests. The river was 100 per 100 milliliters and the pond was 5900 for a hundred milliliters which was a lot higher than Middlesex Stream, which was only 1000 per 100 milliliters.

3. Josiane: Oh, I thought there was the opposite, I thought the Middlesex uh Stream had a lot more [pause] fecal coliform.

4. Valerie: It still makes sense though because the Pond is a kind of a [pause]- it sits there. But then it doesn't make sense with the oxygen if it [pause]- I don't know. If there's so much waste being produced in the pond, then why isn't it hurting the oxygen?

5. Brad: [Grinning] These are called <u>anomalies</u>.[5]

Summary of Episode. In this segment, the teachers tried to work out the relationships among the various measurements Valerie had taken, but met with frustration. Many problems emerged, as it became evident to the teachers that data from one test did not mesh with data from another, that their impressions did not mesh with some of the measures, and that presumed relationships among factors did not mesh with their results. After some disagreement, Josiane and Valerie worked out the direction of the fecal coliform readings: Alewife Pond had a higher fecal coliform reading than the river or the stream. Valerie saw the high fecal coliform result as reasonable, given that the pond "sits there," stagnant and still. The measure in this case seemed to correspond neatly to her observations. But the correspondence broke down as she considered the fecal coliform reading in relation to the DO reading (turn 4), a relationship explicitly addressed in the Mitchell and Stapp (1991) manual that Valerie had been reading: "The main factor contributing to changes in dissolved oxygen levels is the build-up of organic wastes or wastes from once-living plants and animals, and from the feces of animals... As plants die, aerobic bacteria consume oxygen in the process of decomposition. Many kinds of bacteria also consume oxygen while decomposing sewage and other organic material in the river" (p. 24). Valerie noted that a high fecal coliform reading and a high DO reading do not ordinarily go together (turn 4). Brad punctuated Valerie's uneasiness by identifying these apparent contradictions as "anomalies."

Interpretation. Determining the pond's health by measuring various water quality factors became the task that defined the teachers' work and structured relevant phenomena for investigation. In their initial attempts to make sense of Valerie's readings, the group quickly found that the actual measurements they had obtained using the DO and other instruments could not easily be made to correspond with either the features they had observed at the sites or relationships among water quality factors they had assumed. The measurements, in short, lacked transparency, as did the sites themselves. At any given moment, it seemed as if the tests or the pond could anchor an interpretation or dislodge it.

As the group talked, measurements, measured phenomena, field observations, and models were in motion around one another, the teachers' intention to use the tests to describe the bodies of water objectively notwithstanding (cf. Lynch, 1991; Woolgar, 1990). We see this at various points in the transcript in the way that Valerie interpreted the pond and measurements with respect to each other. In turn 2, to correct Josiane's construal, Valerie used the fecal coliform reading as a description of the pond as a whole: "The river was 100 per . . . and the pond was 5900 . . . " In turn 4, she cited conditions at the pond to give reason to the same reading: "It still makes sense though because the pond . . . sits there." In turn 4, her speculation about the chaotic relationship between fecal coliform and DO levels at the pond brought the measures, the group's observations of the pond, and the underlying model into conditional contact, simultaneously drawing each into question: "If there's so much waste being produced in the pond, then why isn't it hurting the oxygen?" It is as if here Valerie was interrogating the model—that is, of dependencies among factors in an aquatic ecosystem—in relation to the particulars of the site, that is, how closely do the theoretical relationships among factors in an aquatic ecosystem express the world of *this* pond?

The teachers' experience ran counter to the logic of measurement as conventionally depicted and as specifically presented in the Mitchell and Stapp (1991) manual, which guided much of their work. The manual presents the procedure of a water quality index (WQI) as a straightforward "translation" of test results into weighted values that are then added together to derive a conclusive value for water quality.[6] It implies, as do most textbooks, curricula, and other traditional representations of measurement practice (Kuhn, 1977/1961), that there is an inherent isomorphism between measurements and measured phenomena, and that measurement is in some sense a generalized method governed by rules unconstrained by content and context (Lynch, 1991).

The WQI itself is thus emblematic of a kind of resource encountered in scientific practice, as well as in the classroom, that is assumed to be transparent in its use and meaning. However, the WQI, like any historically, socially, and culturally constructed tool (Goodwin, 1995; Latour and Woolgar, 1986; Lynch, 1991; Wenger, 1990), represents the integration of various instruments; methods with their constraints, tradeoffs, and assumptions (weighting, sampling, margins of error, etc.); and relevant bodies of theory. As this and subsequent episodes suggest, very little of this background, if any at all, is transparent, especially to the inexperienced user. According to Latour and Woolgar (1986), this disjunction is in a sense the goal of scientific activity: the creation and maintenance of "items of knowledge distinct from the circumstances of their creation" (p. 259), which they called "black boxes."

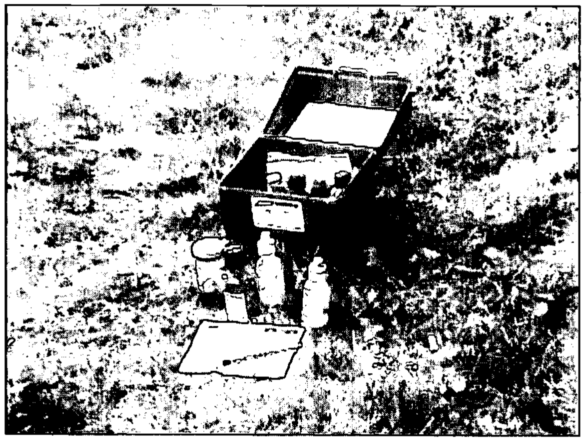

Figure 1

But, as the teachers quickly discovered, achieving a correspondence between the measurements and the pond implicated more than a quantitative operation of translation, of following the procedure and performing the required calculations. In this segment, they sometimes implicitly, sometimes explicitly questioned aspects of their measurements' reliability (turns 2, 6), presumed relationships among the measures (turn 4), and the dynamic interplay of factors in and around the pond (turn 4). In the teachers' work, in short, measurement devices and associated models of theoretical relationships could not be taken as given; nor could they be understood in isolation from one another. They thus became as much an object of inquiry as the pond and, as such, a point of entry into scientific practice. What the teachers began to unfold, through their interactional work, was the tremendous complexity encompassed by the black box of DO, including matters of technique, embodiments of theory, and so forth.

The teachers' conversation about Valerie's initial measurements also indexed their sense of their own shifting relation to scientific practice and knowledge. This can be seen in Brad's evaluation of the group's struggle in turn 5 ("These are called *anomalies*"). His meaning was ambiguous, in that it pointed in several potential directions at once. Were the inconsistent readings ecologically interesting anomalies or mere mistakes in measurement? Was Brad aligning their work with that of scientists or parodying it as a weak form of the "real thing"? On the one hand, Brad may have been simply noting that they had two measures in conflict with the predicted pattern, a classic example of an anomaly, although not necessarily a theoretically interesting one (Kuhn, 1977/1961). On the other, the group had persistently worried about the "reliability" of their measures and their methods, which was in part a worry about their own competence in performing the tests and in part a worry about whether or not they could legitimately view their work as "scientific." Brad's irony, in short, put the teachers' work into contact with—at the same time that it marked their distance from—the larger, and still mostly hidden, world of ecological theory and practice.

Epilogue. The group continued to discuss Valerie's measurements, identifying more troubles as they talked. In the end, at Brad's suggestion, they decided tentatively that they would each run each of the tests on the same samples. While agreeing to this course of action, Valerie remained skeptical: "They'll probably be wildly different, actually." Neither the measurements nor the pond were very stable at this point.

Episode 2: "... we're finding that the pond has got a lot of richness ... " (3/9/92)

The overarching issue of how to determine the pond's "health" filtered through the teachers' work in various ways. In this episode, we examine the teachers' efforts to integrate a voice of scientific authority into their ongoing activity, as one move among many to penetrate scientific understanding of the phenomena under study. Brad reported on a conversation he had with a friend of his, Fred, a marine biologist, about the role of DO in assessing water quality and the overall health of a body of water. In the following segment, the teachers' engagement with Fred's ideas helped focus and complicate their work and understanding, while at the same time bringing them into closer contact with the ideas and practice of ecology. Rather than providing "answers" to some of their basic questions about DO as an important determinant of water quality,[7] as Brad had hoped, their consideration of Fred's ideas seemed to invite them deeper into the measurement and meaning of DO. In this episode, they specifically examined the ways in which notions such as "good" and "bad" might apply to aquatic ecosystems and to the pond in particular.

1. Brad: [referring to his notebook] He (Fred) went on and said that dissolved oxygen or the lack of it is only one indicator of how good the water is. You could still have a lot of dissolved oxygen and still have terrible water, for the sake of other contaminants that may be in it. Conversely, you could have low dissolved oxygen relative to other things, but if the water is free of a lot of other impurities, it still might be, good water as opposed to bad water, yeah. So he was
2. Josiane: =(Although I, I thought) I don't know, that pond sure has a lot of *life* in it, I don't know! [laughs]
3. Brad: Well that's what his comments suggest
4. Josiane: Mm-hmm
5. Brad: =that, you know we're al- we grow up thinking, "Well, if you're going to drink any water, drink the water out of the fast moving stream."
6. Josiane: Right
7. Brad: You see-
8. Josiane: //So (it's/that's) good for some things
9. Brad: //Uh yeah, that's right, but it may not tell the entire story. And indeed we're finding that the pond has got a lot of richness, or that there is more going on- there may be some nutrients in there as well as some contaminants.

Summary of episode. As Brad understood from his talk with Fred, the measurement of DO alone would not necessarily provide a direct indication of the health of a body of water, that is, "how good the water is." Moreover, the group had informally assumed that high levels of DO would be associated with "healthy" sites, but, according to Fred, this was not necessarily the case. Brad's understanding now was that high (or low) DO might be measured in water that was either "good" or "bad." Brad's conversation with Fred opened up for him the idea that in the practice of ecology the interpretation of DO measurements was strongly contingent on the presence/absence of other factors, which he framed as "contaminants" or "impurities." This perspective also implied that the water in the pond was itself potentially more complex than the group had first thought or been led to believe, whether by the tests themselves, the water quality index, the group's measurements, or their own prior experiences, assumptions, and observations.

Interpretation. In their encounter with Fred's ideas, the teachers were able to open up the category of what it means for a pond to be "healthy" and to bring to light the otherwise tacit assumptions and relations developed through their prior experiences and understanding of water. We see in this episode that their efforts to cope with the connections and disjunctions between what we might call "everyday" and "scientific" ideas also entailed ongoing construction of their own relation to these ideas, that is, their identities (cf. Lave and Wenger, 1991). We organize our analysis of this integral relation between learning and identity in two parts: (1) the teachers' expanded use of categorical distinctions, such as "good" and "bad," to describe a body of water, and (2) their use of reference in constructing the various social realities that were brought into play through their concerted work to describe the water at Alewife Pond.

In this episode, Brad and Josiane reconfigured notions of "good" and "bad" water in relation to the measurement of DO, the presence/absence of other factors, and observable qualities of the pond. In so doing, they elaborated what it might mean for a pond to be "healthy" in an ecological sense and what specifically would be required to make sense of any given DO reading. Beginning in turn 1, Brad explained to the others that DO could not be assumed to be singularly deterministic in assessing the health of a pond. How one assesses the meaning of a DO measurement depends in large part on the presence or absence of "other contaminants." High DO could be found in "bad" water; concomitantly, low DO could be found in "good" water. In light of Brad's explanation, Josiane was moved to comment on the abundance of life they had observed at the pond, which, when juxtaposed with their other observations (e.g., the pond's odor, stasis), perfectly captured the puzzle with which they were confronted: Was the water "good" or "bad," and, in either case, "good" or "bad" for what purpose? In turn 5, Brad recast his childhood understanding that fast-moving streams equate with "good" water, here meaning water suitable for drinking. Josiane, in turn 8, built on this by connecting DO's significance to variable purposes (" . . . good for some things"). In turn 9, Brad suggested that the anomalous pond might be emblematic of just the sort of complexity hinted at by Fred, that no one indicator can "tell the entire story." In the process, he invented a new descriptor, "richness," to capture this newly appreciated potential complexity.

In this exchange, then, notions of "good" and "bad" water shifted and were indexed specifically in relation to the world of the pond, the teachers' experience, and water quality measurements and their presumed interrelationships. These indexings culminated in Brad's final turn, when he remarked that the pond "has got a lot of richness." "Richness," as Brad used it here, was a consequentially ambiguous predicate, that is, it encompassed potentially both "good" (nutrients) and "bad" (contaminants) elements. Under the influence of Brad's account of Fred's perspective, "good" and "bad" became contingent qualities requiring specification; they were no longer, as Sacks (1992) called them, "standardized categories"[8] that could be used without specifying what was meant by them in this particular case. In this new light, they were being respecified as a kind of dimensionalized measure; as such, they constituted a first unpacking of what our everyday notions of "healthy" and "unhealthy" might mean when talking about a pond and, specifically, *this* pond, in the terms of an ecologist.

Thus, the respecification of "good" and "bad" gave shape to a different measurement game, one constituted by the group's emerging sense of the complexity of ecological theory and practice, and one that was other than straightforwardly transparent or descriptive, in which methods and measurements were tightly coupled to both visible and invisible constituent elements of the pond and their complex interrelationships. In addition, the group's consideration of Brad's report suggested, perhaps more implicitly than explicitly at this point, the potential limitations of the water quality tests themselves; while they provided the teachers with measurable access to the world of the pond, they also shaped what they were able (or not) to see there (Goodwin, 1995). It remained for Brad, Valerie, Josiane, and Meg to explore further the contingent nature of their measurement activity and the system of relationships to which such states as "good" and "bad" and their particular test results are indexed in the practice of ecology.

The teachers' efforts in this episode to construct possible meanings for "good" and "bad" water were integrally connected to how they positioned themselves in relation to "everyday" and "scientific" understanding and practice.[9] To explore this, we examine the constitutive effect of reference in the teachers' conversation (cf. Hanks, 1996; Ochs, Gonzales, and Jacoby, 1996). By this we mean how, in any act of referring to the world, a speaker engages himself or herself in a network of social relations, that is, he or she takes up a position within the world and also, whether explicitly or implicitly, positions others within it. This positioning is inseparable from knowing (Lave and Wenger, 1991); we maintain that it is an essential and often neglected part of what it means to learn to "see into the subject matter" of science. Here we examine specifically how Brad and Josiane constructed their own and their colleagues' membership in the various social worlds—i.e., ecological practice, the teachers' work, and childhood routines—that were brought into play through their work.

In reporting his conversation with Fred, Brad began by addressing a collective yet indeterminate "you" (turn 1). Neither "we" nor "they," this "you" helped construct a hypothetical world ("you could have . . . ", "if the water is free . . . ", "it still might be good . . . ") in which the assessment of DO was embedded in a complex system of possible relationships, a system Brad was working to understand even as he was speaking (e.g., "it still might be good water as opposed to bad water, *yeah. So* he was—"). In its indeterminateness, "you" marked a zone of ambiguity, of blurred boundaries between intersecting worlds: Fred's world of ecological practice and understanding and the teachers' world. Who among those present might actually participate in making these complex, embedded assessments remained, however, indeterminate, part of a possible relationship to the world of ecological practice.

Josiane responded immediately to Brad (turn 2) in the voice of an uncertain "I," through which she expressed her own doubts about how to weigh the abundance of life they found at the pond, as well as their other observations and measurements in relation to Brad's report. Brad, in turn 5, then introduced an inclusive and collective "we," which embraced a vast public, including all of those present, as well as others like them who "grow up believing" simple, self-evident, one-dimensional truths. Here, there was no question of who belonged in this group, which was typified by generalized propositions and routinized, unproblematic ways of seeing the world. Brad, rather than endorsing this habit of mind, recast it in the light of his shifting sense of potential complexities.

Finally, in his last turn, Brad reconstituted the "we" of this particular group and its relation to his sense of Fred's world. This last "we" belonged to those who were immediately present, who with their measurements and observations "are *finding* that the pond has got a lot of richness . . . " [our emphasis]. In this way, Brad in effect located the group's experience within his emerging understanding of Fred's world and in so doing identified them as legitimate participants in the practice of science: What he had ironically called "anomalies" in their earlier work, he now redescribed in terms of a concept of "richness," which he derived from his conversation with Fred about the practice and theory underlying water quality measurement.

Thus, we see in this segment how the teachers continually constructed their own and their colleagues' shifting and heterogeneous relation to "everyday" and "scientific" practice. Making sense of the various intersecting social worlds at play in their work entailed taking up a position (or positions) in relation to them, however indeterminate these were at times. This positioning was itself subject to minute-to-minute reevaluations, as the social worlds of ecological practice, the teachers' own work, and childhood routines were themselves reconstituted through the teachers' moment-to-moment sense-making. Thus, the teachers' increasing engagement and participation in intersecting social practices was inextricably tied to their emerging sense of the complexities of pond ecology. In the words we used in the introduction to this paper, learning to see into the subject matter of pond ecology was thus integrally related to becoming different kinds of participants in the practice of science.

Epilogue. Later in this same session, the teachers considered some DO retests of one sample each from Alewife Pond and Little River, comparing them to their January readings. The two DO readings from the pond were the same, whereas those from the river differed. The teachers' discussion of these results left them unsettled. The results from the pond seemed to suggest some stability, lending some confidence to their procedure, but the contradictory results from the river undermined this confidence. The problem of what the numbers meant thus persisted.

By this point, Valerie had come to distrust their numbers. She resisted a suggestion to graph the data, concerned that she would then have to assume that "the numbers are correct." Perhaps reflecting on Brad's report, she also wondered aloud about the need for a norm as a specification of "what is healthy": "We don't know what they [the numbers] mean. We can only compare them to each other . . . [not] an established norm, or what is good, or what is expected, or what is healthy." She thus brought out an aspect of defining "what is healthy" that was backgrounded in the group's discussion as they worked to respecify what is "good" and what is "bad."

By the end of this episode, the measurement activity in which the group was engaged had shifted. Specifically, questions regarding what DO is about and how it is related to other elements in a pond were now located within a complex world of possible relationships, purposes, and activity. In addition, both "scientific" and "everyday" worlds of theory and practice—the possible intersections between them and the teachers' shifting relations to them—were fully interanimated in the teachers' work.

Episode 3: "At that time, at that temperature." (5/18/92)

In the following weeks, Valerie's group and the other teachers shared their work to date in whole-group presentations and discussed how they might best continue. Teachers and staff jointly decided to spend the remaining meetings of the semester developing more focused studies, which would culminate in two weeks of summer work. Valerie, Brad, and Meg wanted to continue their water quality testing but decided to concentrate on DO. Drawing on their prior work, they sought to unpack the complex world of ecological theory and practice implicated in the "black box" of the DO test kit, specifically by focusing on how it worked, what it was measuring, and how DO related to the larger study of aquatic ecosystems.

As a first step, Valerie looked for a DO test norm to cope with the dilemma of comparing test results "only to each other." In Mitchell and Stapp (1991), she found what appeared to be just such a standard. The information facilitated the group's practical work, at the same time that it further complicated their understanding of DO by giving rise to new problems of interpretation. Valerie read in Mitchell and Stapp (1991, p. 25) that DO results must be related to water temperature and converted to "percent saturation" values for proper interpretation. This is because the rate at which oxygen dissolves in water varies with temperature: the warmer the water, the less DO it can hold. Thus, a lower DO measurement, if taken from relatively warm water, can still indicate a high "saturation" level. Relating DO to temperature provides a means of comparing the DO in samples taken at different temperatures. Interestingly, the norm specified the terms of comparison between samples in a way unanticipated by the teachers, that is, in terms of temperature. In this way, it also expanded their sense of the complexity of an aquatic ecosystem.

In Mitchell and Stapp (1991), Valerie also learned that bodies of water with a DO level of 90 percent saturation or above are considered "healthy." Encouraged, she conducted a DO test on a lake near her home. She hoped to confirm her informal sense that it was "healthy" (i.e., used regularly for fishing and recreation) with the evidence of test data, and, reciprocally, to explore the meaning of the 90 percent criterion itself. She was in a sense simultaneously testing the test, testing the lake, and attempting to establish some base of comparison for the pond. The following transcript is taken from a meeting in which Valerie presented the results of this DO test to the rest of the project teachers and staff. Mark, Faith, and Ann are staff members; Glen is a participating teacher.

1. Valerie: It just kind of went along with what we were saying, I mean, just eyeballing something and saying, this looks healthy, this looks unhealthier. And the lake by my house appears very healthy and it has um just- especially compared to like Alewife Pond. And so Alewife Pond was below the- 90 percent saturation is considered healthy or 90 or above unless it's due to cultural eutrophication.[10] And so, I was pleasantly surprised, but not too surprised when I got the results yesterday and I thought, oh, okay, well, this kind of confirms, I expected to get a good score for this lake.
2. Mark: This would be high on the- ?
3. Valerie: Yeah, I mean, it doesn't really confirm our hypotheses yet. We're still looking into it.
4. Faith: And what was the score for Alewife again?
5. Ann: It's right there, seventy-one percent.
6. Valerie: Eighty-eight? Oh yeah, seventy-one.
7. Glen: Oh.
8. Valerie: Seventy-one percent oxygen.
9. Ann: At sixty-two degrees.
10. Glen: So that's an indicator of ill health?
11. Valerie: At that time, at that temperature. So I think what we're figuring out is we're going to have to do- at least what I'm thinking is, we're going to have to do more tests on the same bodies of water to see if the percent saturation remains stable over time. And that will tell us more than just one reading at one temperature at one time of day.

Summary of episode. Valerie reported that the DO test at the lake near her home yielded a result of 100 percent oxygen saturation. She was pleased that this result confirmed her general impression that the lake seemed "very healthy," especially compared to the pond, unless it reflected processes of cultural eutrophication. She explained the DO finding for Alewife Pond, a saturation level of 71 percent at a temperature of 62 degrees, as limited by her sampling procedure, that is, it represented only one sample at one time of day and at one temperature. She went on to say that more samples would be needed to "see if the percent saturation remains stable over time."

Interpretation. In this episode, Valerie brought some closure to old dilemmas and opened up some new terrain, hinted at in the group's earlier work and conversation. In turn 1, she indicated that many of their earlier questions about measurement technique and the correspondence of test results with observable features were now resolved, with the possible exception of complications in interpretation due to processes of eutrophication. Her uneasiness in Episode 1, that repeated tests on the same samples would be "wildly fluctuating," gave way to a confidence embedded in a system of relationships involving the measurement device, measurement norms, bodies of water, and field observations, as well as practical mastery of the test procedure itself. In this sense, the world—of the pond, the DO measurement device, and their relation to each other—was becoming more orderly.

But these worlds were not yet fully coherent, that is, new perspectives on the pond as a particular kind of system and the use of the DO device emerged, as Valerie noted in her responses to Mark in turn 3 and to Glen in turn 11. Asked by Glen if the reading for Alewife Pond was an indicator of ill health, Valerie constrained her interpretation of the finding. Glen, who was inexperienced with DO much as Valerie had been at the start of their investigation, wondered if the status of the pond could be fixed with a conclusive statement. Valerie, in light of her previous experience with DO, the group's discussion of Fred's ideas, and her research on a measurement norm, resisted this move. In this sense, the norm she found and used, while solving certain problems of comparison and interpretation, helped her see additional complexity in the theoretical assumptions underlying the DO test, the physical character of the pond, and the practice of DO measurement itself. One reading would not suffice; more tests would be needed to determine the stability of DO levels over time.

Thus Valerie foregrounded time, representing fluctuations in temperature throughout a 24-hour period, as a critical factor in the life of the pond and in the measurement of DO. The DO measurement itself was now firmly situated in a distinctively temporal world. Its coherence, rather than deriving from a generalized logic of measurement, derived from its particular subject matter—the ecological complexity of a body of water—and its specific use, that is, how the teachers prepared and used the test, collected and fixed samples, multiplied readings, interpreted results, etc. (Lynch, 1991).

Valerie's sense of the system she was attempting to measure was, in short, becoming more attuned to the complexities suggested by Fred, that is, of the pond as a dynamically interacting system, and to the hidden assumptions and model that comprise the DO inscription device. Her response to Glen paralleled the shift in perspective that Brad helped foster in Episode 2, when the group's notions of "good" and "bad" were respecified in light of Fred's ideas. In addition, we note that, in a manner reminiscent of Episode 2, Valerie, in turns 3 and 11, situated her work and thinking squarely in the collective "we" of this group of competent practitioners (" . . . it doesn't really confirm our hypothesis yet. We're still looking into it"; " . . . what we're figuring out is . . . "), introduced by Brad at the end of the earlier episode ("And indeed we're finding that . . . "). She also recognized the presumption in her proposed next move to "do more tests on the same bodies of water" by marking it in turn 11 as her own thought ("at least what I'm thinking is . . . "). The possibility of doing repeated samples, while scientifically justified, was often practically difficult, given the realities of the teachers' lives. This difficulty became the fodder for jokes about who in the group was going to do what, which is perhaps the surest sign of increasing participation in a community. It takes deep and practical experience inside a practice to know what to avoid and when. These practical difficulties aside, the teachers' increasing mastery of the DO test, it seemed, created new problems even as it solved old ones.

Epilogue. The academic year seminar was coming to a close. At the last meeting of the year, the entire group of teachers, feeling somewhat fragmented in their individual group investigations, decided to organize their collective work around a single question: Is Alewife Pond healthy? They formed three working groups, each of which would dedicate itself during the two-week summer seminar to studying a specific aspect of the pond. In the context of this grand plan, the groups would coordinate their data collection and findings. Brad continued his interest in water quality but elected to study another factor, while Valerie and Meg continued their investigation into DO.

Episode 4: "It should go like this and it pretty much basically does . . . " (7/7/92)

Taking advantage of the all-day summer meetings, Valerie and Meg developed an approach to testing that would satisfy Valerie's sense that they needed to do repeated sampling over time at the pond to develop a stable DO level. They then sampled from specified locations around the pond and at predetermined times of the day during the first week of the seminar (see Figure 2). After conducting a week's worth of DO tests, Valerie and Meg met to discuss a pair of graphs (see Figures 3 and 4) Valerie had created to see how the DO level of her samples varied in relation to water temperature at Alewife Pond.[11] Figure 3 represents the "raw" DO readings—that is, the value that immediately results from reading the DO test—for each sample in relation to its water temperature. The DO values are given in parts per million (ppm). Figure 4 shows

Figure 2

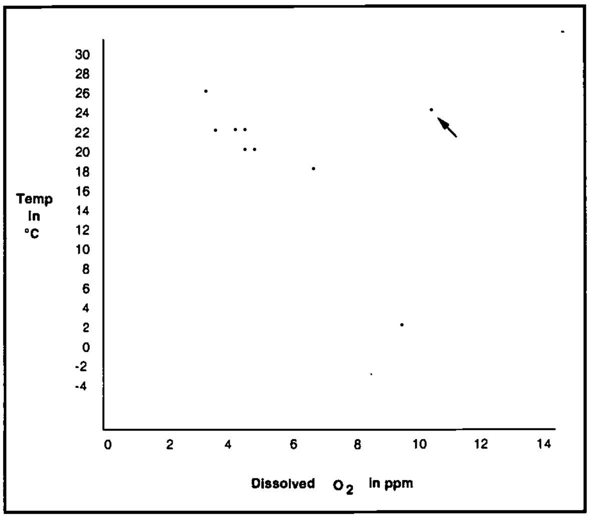

Figure 3

DO as related to temperature at Alewife Pond

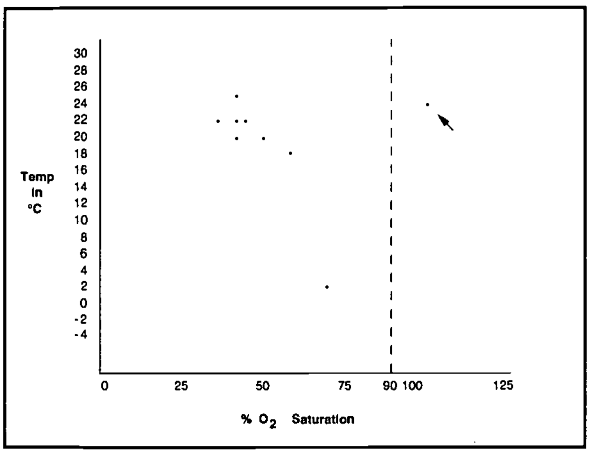

Figure 4

% O2 Saturation as related to temperature at Alewife Pond

the percent saturation value for each sample in relation to temperature; it is a value derived from using the standard level of oxygen saturation chart to determine percent saturation levels for measured DO readings (in ppm) at given temperatures. According to Mitchell and Stapp (1991, p. 25), a value below 90 percent means that the tested body of water may have large amounts of oxygen-demanding materials (e.g., organic wastes). The arrows on both graphs denote "sample number five," which became the subject of considerable discussion. Valerie also had at her disposal a hand-drawn map of the pond, on which she had noted the location of each sample and its physical characteristics.

1. Valerie: In this one [Figure 3]- I don't- the more I think about it- the more it doesn't make any sense. Well this one [Fig. 3] I- I did the dissolved oxygen reading as related to temperature [long pause] to show that- okay obviously- when the temperature is higher there's less dissolved oxygen [writes on Fig. 3]. But even when the temperature is lower [pause] here [pause] there's still- [long pause] that doesn't show anything. Well that- well- when the temperature is lower the dissolved oxygen is higher so that it should go like this [traces imaginary curve on graph] and it pretty much basically does. Except for this one [refers to a point for which both DO value and temperature were high] and that's the one we just did. It's way off over there.

2. Meg: That's this one?

3. Valerie: Right, that's number five [labels graph]. Now on this one [takes out Figure 4] I did- actually I guess this does make sense to me. This shows the um percent oxygen saturation um [pause] as related to temperature. And um the higher the temperature the lower the percent oxygen saturation in this pond. Except for that one- except for number five. But it shows that all of the readings at any temperature except for this one [number five] are below the ninety percent cut-off for what's considered a //healthy pond].

4. Meg: //healthy pond].

5. Valerie: So that's why I did that one [long pause during which she examines Fig. 4]. Now it's interesting that all these [referring to all points *except* number five on Fig. 4] were in the shade [smiling].

6. Meg: Except for this one.

7. Valerie: Except for number five.

8. Mark: And you pointed out that that area is probably exposed for most of the day.

9. Valerie: Yeah, well, there was a ton of plants in there, too, so I don't know how to interpret this [pause]

10. Mark: Hmm it's really

11. Valerie: because I scooped out- I mean you saw where I scooped it out. There was- I had to squish the plants down in order to get water.

12. Mark: There's a lot of floating like algae-looking things?

13. Valerie: Yeah, choking, I mean I'm using words that make it sound bad [laughing], words to support my hypothesis. I didn't say flourishing. I said choking.

Summary of episode. Valerie developed a reading of Figure 3 that highlighted the expected relationship of DO to temperature, save for one point which was "way off over there" (number five). She saw the second graph (Figure 4) in two ways: first, as confirmation of this pattern, and second, as evidence that, with the exception of number five, all the readings, regardless of temperature, were below the 90 percent cutoff for what is healthy. As Valerie continued to examine her graphs and map with Meg, she brought into view specific conditions at each sampling site, especially differences in illumination and vegetation between the sites below the 90 percent cutoff and the one aberrant site above it.

Interpretation. In this episode, we see how the act of reading the graphs inscribed relations among various resources that had come to figure significantly in Valerie's ongoing work: models of ecological relationships; embodied experience using the DO measurement device; features of the site; the structure of claims; texts; and features of the graphs themselves. Valerie's effort to read the graphs rendered some of these relations orderly and left others still open to investigation. In the process, it brought to the foreground a spatial view of the pond, one related to specific geographic features of the sampling sites, that complemented and complicated the temporal view highlighted in her work in the previous episode.

In turns 1 and 3, we see Valerie working to develop an interpretation of the graphs. In doing so, she read the graphs and the underlying model of the relationship between DO and temperature in terms of one another, as in this segment from turn 1 in reference to Figure 3: "But even when the temperature is lower [pause] here [number five], there's still—[long pause]—that doesn't show anything. Well that—well—when the temperature is lower, the dissolved oxygen is higher, so that it should go like this [traces imaginary curve on graph], and it pretty much basically does." This interanimation of model and graph can also be found in Valerie's reading of Figure 4 (percent saturation related to temperature). After confirming the same relationship as in Figure 3, she focused on a second reading of the graph in terms of determining "what's considered a healthy pond" by using the 90 percent cutoff (which is both a part of the model and a visual feature of the graph) to bundle and interpret all the readings to the left of the cutoff as being indicative of an unhealthy pond ("all of the readings at any temperature, except for this one, are below the 90 percent cutoff for what's considered a healthy pond").

As soon as Valerie stated this conclusion, however, she refocused on the data and began to move away from a world structured by the DO x temperature model and graph relations and back to the actual sampling conditions at the pond (turn 5). She noted that all the values, except for number five, "were in the shade," an interesting fusion of data points and real-world locations. Meg focused on number five, and Mark followed this by noting that Valerie had said that the sampling location was "probably exposed for most of the day." Valerie, in turn 9, recalled the abundance of plant life in the sampling location, implicitly suggesting that the exposed (and thus photosynthesizing) vegetation might explain why the DO reading from that spot was so high. She went on to narrate vividly what it was like to take the sample (turns 11 and 13), punctuating her account with a description of the "choking" plant growth she found there. This characterization echoed descriptions of eutrophication she had found in various texts: In an ecosystem undergoing eutrophication, excess nutrients promote excess or "choking" plant growth. Valerie, very much aware of the constructive nature of her work, laughingly acknowledged her own agency in creating this negative characterization ("I'm using words that make it sound bad . . . I didn't say flourishing. I said choking").

In this episode, we see that as Valerie worked to make sense of the graphs, their meaning was anything but transparent. Indeed, they became a dynamic, interanimated space in which she brought together DO-temperature relations, models of aquatic ecosystems and eutrophication, conditions at the pond, visual features of the graph, and her own embodied experience collecting water samples. As Nemirovsky, Tierney, and Wright (in press; see also Latour, 1990) discussed in their study of graphing, Valerie's graphs merged the here and now of her sense-making with selected features of the represented site, selected features of the graphs, experiences that went into representing sampling events, and embodied experiences using tools, relevant texts, and interpretive frameworks. In this sense, "reading" the graph was an act of complex "seeing into" the world of the pond, the world of her own action and sense-making, and the world of ecologists' inscription devices and practices, in a way that was not possible when Valerie first encountered descriptions of aquatic ecosystems and DO measurement devices in the Mitchell and Stapp (1991) manual.

Epilogue. The graphs, while perhaps clarifying some aspects of Valerie's work and understanding, on a second look raised new questions about the particular measurements, the complex geography of the pond itself, and the sampling methods. The world of the pond, the DO device, and the idealized world of ecosystem dynamics further complicated one another. Valerie was left with another puzzle, one that in the days following literally led her back to the pond to take additional samples.

We conclude the narrative and analysis of the DO study with a transcript from the final day of the summer seminar, July10. During their 10 days of work, Valerie and Meg took many samples at the pond. In the end, their results showed a pattern of low DO levels in the early morning (below 50 percent saturation) and high levels later in the day (100 percent saturation). On the last day of the seminar, each group shared its findings and questions. In the following, Valerie commented on their findings and responded to questions. Gilly is the project's biologist with a research background in chemical ecology; George is a science educator, trained as a chemist.

1. Valerie: I tried to find information on whether this large range of dissolved oxygen was considered healthy, because it seemed to me like if it started really low, rose really high and then crashed, that would cause a lot of extreme conditions for the fish and other organisms, so I couldn't find anything on it, but [pause]

2. Gilly: Val, do you think that could be why on Glen's group's scale that the fish- you have to look at the fish-kills at dawn? Is that the sort of thing?

3. Valerie: Yeah, I think so, because the dissolved oxygen is used up overnight, and there's no photosynthesis replacing it. Also that and of course it depends on where we took our samples, like Meg said, we took them near the shore, where there's a lot of algae floating there and they're photosynthesizing, with the light on them and, we're obviously- if we take water from above a big clump of algae it's probably going to have a lot of oxygen in it.

4. George: So you're guessing that if you'd taken oxygen levels farther out in the pond they would have been even lower.

5. Valerie: I think we could have come to more conclusions. I don't- they may have been- they may have been less extreme.

In her commentary, Valerie introduced a shift in the ontology of DO. Formerly confined to levels above and below a certain cutoff, DO at the pond is now described in terms of a "range," the need for which resulted directly from her measurement activity. Indeed, this finding led her back to the pond, in this case metaphorically, as she imagined what it would be like for "fish and other organisms" to experience such swings in DO levels. Likewise, she qualified her reply to Gilly, based on a model of the DO cycle, by reminding herself and her audience that their sampling method limited their conclusions. George, in his question, proposed that "farther out" in the pond might yield more definitive results, "even lower" DO levels. But Valerie, knowing better after her many hours of progressive engagement with DO, resisted this speculative move, preferring a conjecture that implicitly retained the possibility of some as yet undiscovered messiness even "farther out."

In summary, this brief exchange both recapitulates and extends the multilayered quality of Valerie's experience. No thing and no one is quite the same as they were when they started out. The pond itself and the DO measurement device have become different sorts of things for Valerie, less closed and more open along many dimensions. Static characterizations of the pond as "healthy" or "unhealthy" in terms of *an* indicator have given way to a sense of the pond as a dynamic system of interrelationships. While short on definitive conclusions, in this last episode Valerie presented herself as someone who continued to pose questions and resisted easy answers to complex speculative questions. It was thus out of appreciation for the sense of complexity that had emerged through their work that Valerie later in the summer, in the context of an interview, offered a critical but informed stance toward their study: "The end result is we can't come to any conclusions." This "we," despite the frustration of not having reached any definitive conclusion, took up a position from within the practice of ecology—a "world of involvements" (Taylor, 1995)—rather than from outside.

Postscript to the Case Study

For Valerie, the experience of learning science was further embedded in a larger practice of classroom learning and teaching. As she engaged with particular problems in her own learning, she would sometimes wonder what these suggested about her own experience as a learner, her children's experiences as learners, and her own practice as a teacher. One such moment occurred on 5/18/92 (Episode 3), just after she had discussed the DO test at the lake with the entire group. After sharing their work, Valerie, Brad, and Meg went on to discuss her DO results. This led to a conversation about the percent saturation scale itself. The teachers became frustrated because, although the 90 percent criterion had facilitated their work by providing a standard of comparison, it remained a black box. Valerie complained, "It just tells you below 90 is bad, above 90 is good." The Mitchell and Stapp (1991) manual and other texts the group consulted were silent on the standard's history of development, that is, the assumptions, models, bodies of theory, methods, and constraints that went into its design. Having successfully employed a tool of ecological practice, they now wondered just what it was telling them about the sites and about aquatic ecosystems. As they confronted this newest interpretive wrinkle, Valerie linked their situation to ones she imagined her students must grapple with regularly, which then reflexively returned her to their own plight.

1. Brad: We may be trying to reinvent the wheel, maybe somebody's already got these answers and they're down very clear and we just have to find 'em. It just seems to me- it's hard to believe there should be so much mystery about this, to me.
2. Valerie: Well a lot of times, they just give you a test and say, "Do this, and your results tell you this." And they don't tell you what (they) mean.
3. Brad: I know!
4. Valerie: And I think that comes up a lot in school because, you know that kids will say, "Well, why do we do this?", and it's so difficult to explain at that age level or- I don't know. You know that you just have to kind of- you know- explain the best you can and I think
5. Brad: You can tell them it's because of the cosmic swirl

6. Valerie: And I think there's gotta be a better way, yeah, "Because that's just the way it is"- because um- I think there's- it would be better to feel comfortable with what you're working with instead of

7. Brad: =which I'm not

8. Valerie: =just having it handed-handed to us blindly and having us blindly say, "OK, this means that our- this lake is great and this one is not" when it doesn't make sense.

Here, Valerie located herself in relation to her own learning, her teaching, her students' learning, and the discipline of science (perhaps more aptly here, the industry of science education). These social worlds at times intersected in her discourse. In turn 2, she railed against an authoritative "they," perhaps those who author test kit instructions or those who direct the use of such kits, for example, in science education in-services. In turn 4, she linked this practice to school, specifically, to her students' experience of asking "why" they are doing something and the teacher's difficulty in explaining. She seemed uncomfortable here accepting routine responses, for example, explaining the best you can, and, as in turn 6, stated her hope that "it would be better to feel comfortable with what you're working with . . . " The "you" in these turns reflects a composite identity of self and other, including other teachers and other learners. After Brad identified his own discomfort in response to Valerie's hope, Valerie continued in turn 8 with a strong condemnation of customary practice. Here, in her use of "us," Valerie fused her experience as a learner with that of her students, a collective that she thinks *should* resist the unquestioned authority of science. There is a way in which, by locating herself outside scientific authority, she is also speaking from a position inside scientific practice, through her critique of customs—standards, measurement procedures, inscription devices—that, if one begins to question them, do not "make sense" on their face. Valerie is demanding access to what Goodwin (1993) called "professional vision" as an antidote to "blind" following of procedures.

One question, at least, remains for us to address. How, if at all, did Valerie's experience in the pond study articulate with her practice as a teacher? Consistent with our approach throughout this paper, we address this question through a final example, in which Valerie discussed with project staff the significance of an event in her classroom.

In May 1993, a little less than a year after she had completed her work at Alewife Pond, Valerie organized a classroom discussion about plant growth, as part of a unit she was teaching on plant development. In this discussion, she invited her fourth and fifth grade special needs students to discuss the question of where plants get energy for their growth. She was interested in seeing how far they would get toward imagining a process like photosynthesis. The students, to Valerie's surprise, sustained their discussion for a full period.

As part of the unit, all the students had the experience of growing plants in the light and in the closet. Valerie opened the discussion by asking the class whether a plant will "grow very well" if kept in the closet for a few weeks. In the ensuing discussion, three of the students became involved in an argument that significantly complicated the opening question.

One student, Kareem, had a strong interest in science and came into the discussion knowing a lot about plants, so Valerie surmised, from having read about them and having watched T.V. science programs. He argued that only the roots of the plant will grow in the dark, not the leaves or the stems. Two other students, John and Cara, who had comparatively little experience with science, observed that in the closet the roots of their lima bean plants appeared first, but that the leaves were growing inside the lima beans before they appeared outside and, if given more time, would have come out as well. Kareem was unconvinced, his position implicitly being that light is needed for leaves to grow.

In reviewing the videotape of this discussion sometime later with project staff, Valerie's comments showed her still actively constructing its significance, in ways that complicated the relationship of what one knows to learning and teaching. She focused on her students' histories in science, and how these played out in the particular circumstances of the plant discussion.

> What I see in that conversation is my students talking about what they've observed and the way they've interpreted what they've observed. And each student sees- each student experienced the same thing but they all experienced it differently.
>
> Kareem is a scientist. He loves science and he was always thinking- he was usually a step ahead of the other kids in terms of his knowledge. He read a lot of science books when he was in my class and watched a lot of science programs. So I think he may have been coming from his knowledge that plants needed light on their leaves and that there was something in the leaves and the stem which helped the plants make food. And so therefore to him it would be impossible for the leaves and stem to grow in the closet. So it's interesting to think back and try to figure out where they're coming from. Whereas Cara and John are working from a more limited knowledge base, I think really limited to what they had done in class or in other classes before mine. Their reading was not as extensive . . . Cara and John knew that the leaves grew in the closet. They had seen it. And Kareem somehow had ignored that.
>
> I think that what they were saying was confusing Kareem and it was really making him think hard, rather than having him just spit (back) what he thought he knew- that . . . leaves and stems can't grow in the dark because they have to be in the sun.

In her commentary, Valerie touched on several points, in which it is possible to hear reverberations of her own experience in the pond study. She pointed, for example, to the way in which Kareem's canonical knowledge about plants shaped his claims about plants' ability to grow well in the dark, and how Cara and John's perspective served to complicate his point of view. Cara and John specified what grew when, first the roots, then the leaves (which they first observed "inside the seed"). There is some ambiguity as to whether they were saying that the leaves were developing within the seed or whether the leaves actually emerged from the seed in the dark of the closet. Nonetheless, Kareem didn't "see" any way in which the leaves could grow in the dark.

This strikes us as a strong echo of so much of Valerie's experience, in which seemingly standard views, assumptions, and beliefs—whether held by the teachers, explained in texts, or taken as given in the instructions of a test kit—were complicated through embodied experience with a phenomenon (e.g., sampling water at the pond; comparing results from seemingly "healthy" and "unhealthy" bodies of water; reading a graph). Valerie sees in this classroom interaction the different ways in which different children approached the "same" problem. Kareem approached Valerie's question in a certain way, through a background of photosynthesis, of plants needing light to "grow well." It turned out that this way of seeing plants in the context of the students' collective experience of growing plants in the dark actually constrained what Kareem could see. It's not that Kareem was wrong or that John and Cara were right, although it is perhaps worth mentioning that Kareem's approach is often viewed as the only valid one. Rather, Valerie saw the value in both approaches without becoming blind to the possible limitations of Kareem's canonical view when applied in this particular case.

Valerie's perspective on her students' ways of seeing, to us, connects deeply with her own experience in the pond study, specifically in the way she learned to "see into the subject matter" of pond ecology through her engagement with the various conceptual, symbolic, and material resources (e.g., measurement devices; measurement standards; models of aquatic ecosystems; texts; graphs; field sites; etc.) of the discipline. The parallels extend even further, to the ways in which the subject matter is continually reconfigured through learning. As in the teachers' experience with the question of "What is a healthy pond?", the very question the children sought to answer potentially took on new meaning as they made sense of what they had observed: What would it mean for a plant to "grow very well" in the dark? In her discussion of her students' ideas, Valerie suggested that the "answer" to this question entailed distinctions that became relevant only as the children worked with plants and discussed their observations and respective points of view.

Thus, we see in the way Valerie considered her students' various experiences, and the complicating effect of Cara and John's argument on Kareem's thinking, the kind of reconfiguring of the subject matter of plant growth and development that seemed to happen continually in her own work studying the pond. It relates as well to the kind of reconfiguring to which Ball (in press) pointed in her account of Ofala. In the conception of teaching Valerie was beginning to explore, the subject matter of science, rather than being static and ready made, had become a space in which learners' ideas and experiences, Valerie's own ideas and experiences, and the ideas and practices of science interanimated one another.

Concluding Thoughts

In the introduction to this paper, we posed this question, building on Shulman (1986): What is learning for teaching, and how does it articulate with learning the subject matter of science and with teaching science? In this paper, we have described one teacher's experience in a particular time and place, with particular others, particular material, and conceptual resources, in order to bring into view her lived experience learning science. We have done so because we believe such "thick descriptions" (Geertz, 1973) can shed needed light on possible meanings of this idea of "learning for teaching," less as a catalogue of the forms of knowledge one acquires in order to teach than as particular kinds of experiences that afford ways of seeing into learning and teaching from inside a practice, such as science, rather than from outside. We hope, through such descriptions, to lend some sense of actuality to the idea of "learning for teaching," such that, as Geertz (1973) argued in relation to notions of culture, we can think concretely about it and, perhaps what is more important, creatively and imaginatively *with* it.

This move, to describe "learning for teaching" in its material complexity, parallels the move of Ball (1993, in press) to study the complexities that attend accomplished practice and practitioners' efforts to cope intelligently with them. Both moves, to our minds, turn the object of interest within the paradigm of teacher knowledge studies from a noun—knowledge in some sense antecedently known, represented, and then applied (Dewey, 1929/1990), to effect some result we call learning—into a verb—knowing—that is itself constituted by what we know and do and the situation of our knowing, rather than prior to them. In this view, what teachers know both shapes and is shaped *in* practice. This move from knowledge to knowing thus shifts teacher knowledge out of the individualistic space of mind and representation, in which knowledge we somehow "have" in our heads generates action and makes it interpretable, into a realm of situated acting and sense-making in which, as Suchman argued (1987) in her critique of a planning model of human action, any given situation becomes an inexhaustibly rich, even if often problematic, resource for teaching and learning.

This view that knowing cannot be divorced from the messy practices of which it is a part, that indeed its creative potential derives in large measure from mundane, situated acting within a socially, culturally, and historically constituted practice, has also been taken up in studies of scientists' work. That science, like teaching, is a contingent, constructed achievement runs counter to the images of science that predominate in our culture (Latour, 1987; Lemke, 1990; Lynch, 1991). One particularly striking example comes from the work of Goodwin (1993), who investigated how a group of geochemists determined that a particular fiber had turned *jet black*, a decision that was required to stop a chemical reaction. We tend to think of black and white as the most basic color terms, the least problematic, as basic and fixed cognitive categories. Yet, for the geochemists, determining *jet black* was not achieved through the simple application of a single, context-free category of meaning known in advance. Instead, it entailed problematic judgments situated within a matrix of practical work involving multiple perspectives. The existence of a category such as black, much like the category of "healthy/unhealthy" in the teachers' work, did not automatically solve the problem of how what counted as black in this particular case was to be determined. Instead, the geochemists had to specify a sense of black in a way that was appropriate to the activities in which they were engaged. This included, among other things, making use of another, more discriminating set of terms (*gorilla fur* and *orangutan fur*), invented by the principal investigator, which combined both visual and textural dimensions. Goodwin shows, in fine detail, how the notion of what counted as black was not fixed but, rather, was progessively shaped and modified as participants, in interaction with one another, with the evolving situation, and with the tools of their profession, inspected and assessed the changing materials with which they were working.

Valerie's experience in the DO study, while that of a learner and not a practicing ecologist, resonates with both the broad outline and fine-grained detail of Goodwin's analysis. We would add further that analyses of science-in-the-making parallel those of researcher-teachers like Ball and the analysis presented here. Each attempts to make clear what it is like to participate in a practice and construct knowledge within it, whether knowledge of the particular properties of a chemically engineered fiber, a child's understanding of odd numbers, or a teacher's understanding of DO, without abstracting away from the material complexity in which such knowing is embedded.

Notes

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[2]We use the term "managed," not in some technocratic sense of procedural efficiency, but in the more ordinary sense in which we manage our everyday affairs, taking into account what seems important to us at that time and in that place, drawing on our personal, lived experience and what we can make of the experience of other participants, acting with greater or lesser degrees of confidence depending on the situation. Importantly for Ball, these situations in which she finds herself uncertain about how to proceed are always (or necessarily become) self-consciously situations of learning.

[3]The philosopher Charles Taylor (1995) contrasts this sense of the self engaged in the world and with others with a view, dominant in Western thought, of the human agent as the subject of representations about the external world, an inner space or mind definable independently of body, other, or context.

[4]The dissolved oxygen test is a chemical procedure whereby the amount of oxygen dissolved in a water sample is determined by precipitating the oxygen out of solution, redissolving the oxygen compound, and measuring the precise amount of chemical reagent needed to effect a color change. The fecal coliform test is designed to detect the presence of bacteria found in waste from warm-blooded animals, indicative of pollution from sewage or agricultural runoff. Water samples are filtered onto a nutrient-laden screen and subsequently examined for the growth of bacterial colonies. The pH test measures the acidity of a sample and consists of a strip of chemically treated paper, which undergoes pH-specific color changes.

[5]We use the following conventions in our transcriptions:

- ( ) unintelligible word or utterance
- //] overlapping speech
- = contiguous speech
- \- self-interruption
- [ ] expressive, gestural, temporal aspects of participants' interaction

[6]"To determine the WQI, nine tests are performed. These include: dissolved oxygen, fecal coliform, pH, biochemical oxygen demand (5-day), temperature, total phosphate, nitrates, turbidity, and total solids. After completing the nine tests, the results are recorded and transferred to a weighting curve where a numerical value is obtained. The numerical value or Q-value is multiplied by a 'weighting factor' for each test. For example, dissolved oxygen has a relatively high weighting factor (.17) and therefore is more significant in determining water quality than the other tests. The nine new values are added to arrives [sic] at an overall water quality index figure (WQI)" (Mitchell and Stapp, 1991, pp. 14–15). We do not mean to criticize the Mitchell and Stapp manual, on which we have relied numerous times; rather, we want merely to indicate that it is representative of a genre of description and explanation often found in science-related texts. Clearly, its usefulness in any particular situation, like the

water quality measures themselves, is interactively constituted.

[7]The teachers knew from Mitchell and Stapp (1991) that DO was the most heavily weighted factor in the WQI and had an intuitive sense of its importance.

[8]Sacks (1992, Lecture 8) examines such cases as "How's your appetite?" and the response, "Not good," where the response is taken as an adequate, understood description of one's state, that is, a variation on what is taken, without the need for specification, as "normal." He describes "normal" as "a standardized category, where whatever it refers to for any given person doesn't have to be specified to control its use" (p. 58). Importantly, while the category may be standardized, the specific content is not. My "not good appetite" may be very different from yours; similarly, my "normal" does not typically have to be calibrated to "normal."

[9]We are indebted to Rogers Hall for drawing our attention to the constitutive effects of reference in this and a later episode.

[10]Valerie's reference to "cultural eutrophication" was taken from a passage in Mitchell and Stapp (1991), which referred to the special case in which DO results above 90 percent may be indicative of ecosystems that have been polluted by human action (e.g., by agricultural runoff). If this "cultural" input to an ecosystem includes nitrogen- or phosphorus-bearing compounds (e.g., fertilizer), the excess nutrients can artificially stimulate plant growth, which in turn can elevate DO levels in excess of 90 percent saturation.

[11]Valerie's original graphs have been lost. Figures 1 and 2 are the authors' reconstructions, based on videotapes and transcripts of related graphs Valerie shared with the larger group later that summer.

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