Embracing the Essence of Inquiry: New Roles for Science Teachers

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“This is the thing I really get excited about. There are some great ideas here, some really neat projects. Wanda and Joan are working on amphibian decline. Ann is interested in territorial behavior or some sort of feeding behavior in crawdads. That is a good one to study because crawdads are an important decomposer in the stream. We’re looking at what kinds of criteria in a stream make it habitable for different kinds of organisms. And when you see those different combinations of organisms, what do they mean? How do you interpret them? I mean we’re really getting into higher levels of thinking, because we’re looking at different kinds of organisms and interpreting them in terms of stream health.”


As soon as I entered the classroom I was struck by the intense involvement of the students. Although no bell had rung, the twenty high school ecology students were already involved in their work. Aquariums and various animal cages positioned along the side and back counters of the room were the focus of their attention. Every student appeared interested and engaged in various tasks: recording observations in notebooks; discussing their observations with other students; and retrieving materials from a back office area store room. Jake, the teacher, moved quickly in and out of the office area, responding to different students’ comments and questions. As an invited guest I moved from one pair of students to the next, inquiring about their work. Students appeared eager to talk about their projects. The students informed me that the focus of these various projects consisted of trying to create the right environmental conditions to support and maintain a female and male of a selected species. Evidence of success would be reproduction of the pair. The study organisms included native fish from local streams, praying mantises, Australian walking sticks, and slugs. Two boys were carefully placing several large insects into an aquarium. They told me these were leaf-eating insects from Australia. When I questioned if the insects could survive winters in the northwest, one of the boys quickly found...
some books and began to search for the answer. The teacher signaled the official start of class with his words, “Have a seat, please. We’ve got to get going—to get some work done.” At the end of class the boy working with the Australian walking sticks came over to my table, bringing a resource book. Remembering my earlier question, the student told me his source indicated that the insects probably could not survive the northwest winters.

All kinds of questions surfaced from this initial classroom visit, and motivated me to begin a year-long, indepth study of Jake’s teaching beginning the following August. Current national science education reforms advocate teachers create inquiry-based learning environments and state that teachers “focus and support inquiries while interacting with students and that “inquiry into authentic questions generated from student experiences is the central strategy for teaching science” (National Research Council [NRC], 1996, p. 32–33). Yet, there is a paucity of research on how to design instructional environments to promote students’ understandings of scientific inquiry. Orchestrating this kind of nontraditional, inquiry-based instruction is complex, and many teachers have not embraced the essence of this mode of learning in which students begin to “think” scientifically (Fradd & Lee, 1999; Roth, Boutonné, McRobbie, & Lucas, 1999). Progress made in aligning instruction with reform orientations appears slow. Details of day-to-day events in the real world of classroom life are left to the imagination and often frustration of the classroom teacher striving to use inquiry-based strategies. The gap between research and practice may contribute to the disparity between the intended curriculum of the reforms and the implemented curriculum in classrooms.

The purpose of this study was to examine the beliefs and practices of a high school biology teacher who successfully developed and sustained an inquiry-based classroom. The study analyzed the processes of the day-to-day instruction in order to elucidate key aspects of inquiry-based instruction. I began this year-long study of one high school teacher’s classroom with assumptions that I would see “good teaching”, anticipating that many elements of effective teaching would emerge. One might argue that I had a bias towards collecting and interpreting data that would highlight inquiry-related activities. Certainly, I brought to the study a personal knowledge of classrooms gained from teaching in secondary public schools for 17 years. Although I had studied other teachers integrating projects in middle and high school classrooms (Crawford, 1997, 1999; Marx et al., 1994) as well as my own teaching (Crawford, 1996), I did not begin the study with a set of predetermined categories of inquiry-based instruction. Personally knowing the challenges encountered by teachers attempting to design and carry out these kinds of authentic, full-inquiry projects (Crawford, 1996, 1999; Crawford, Krajek, & Marx, 1999; Marx et al., 1994), one broad question guided my study: How does this teacher create a classroom environment in which students appear self-directed and engaged in scientific inquiry? As the study developed through the year, more focused questions included the following:

1. What were the key aspects of this teacher’s instruction?
2. What critical incidents fostered students’ understanding of inquiry?
3. What were the roles of the teacher and roles of the students?

Theoretical Framework

Recent science education reforms [American Association for the Advancement of Science (AAAS), 1989, 1993; NRC, 1996] advocate the design of instructional environments that involve students in learning about scientific inquiry and the nature of science. Research supports teachers engaging their students in pursuing answers to questions important in the lives of
adolescents, as well as those questions important to scientists (Brown, Collins, & Duguid, 1989; Brown & Campione, 1990; Schwab, 1976). Constructivist views of learning lend theoretical support to teachers in facilitating students reconstructing their own knowledge through a process of interacting with objects in the environment and engaging in higher-level thinking and problem solving (Driver, Asoko, Leach, Mortimer, & Scott, 1994).

Popular terms in the world of practicing teachers, including ‘doing science’, hands-on science’, and ‘real-world science’, are frequent descriptors of inquiry-based learning approaches. Translating research to practice may result in reducing the complexity of teaching to simplistic algorithms. There is a danger in equating inquiry-based instruction with the currently accepted notion of “hands-on science” in which teachers provide students with a series of hands-on activities that often are unconnected to substantive science content. The meaning of the term inquiry-based instruction when applied to classroom practice often becomes muddled, and the integrity of the inquiry-based instruction can be lost. Teachers may view their teaching as reform-based, yet their own students’ perceptions of the same classroom environment may be ‘worlds apart’ from that of their teacher’s views (Roth et al., 1999). Inquiry-based teaching strategies need to align with theories of how children learn science which include students revising their understandings through teachers building on students’ experiences (Driver et al., 1994). The integration of socio-constructivist perspectives of learning with hands-on instruction enhances the opportunity for knowledge construction of inquiry (Lave, 1988; Rogoff, 1994; Solomon, 1989; Vygotsky, 1978; Wood, Cobb, & Yackel, 1992).

Efforts to engage students in inquiry-based instruction date back to John Dewey (Dewey, 1938). Dewey believed that children learn from activity, through extended experiences in real-world problem-solving and from discussion with others. In recent years researchers have promoted teachers in their attempts to design and carry out Deweyian-type projects (Krajcik, Blumengeld, Marx, & Soloway, 1994; Roth, 1995; Roup, Gal, Drayton, & Pfister, 1992; Tinker, 1991). Authentic problems that students solve collaboratively differ from traditional school science “experiments” that tend to be verification labs in which students seek the “right” answer. In contrast to completing exercises from a chapter in the textbook, students construct their understandings by solving real-world problems. Efforts towards moving inquiry into the classroom through student-centered, long-term projects have been described by researchers in recent years (Krajcik et al., 1994; Magnusson & Palinscar, 1995; Roth, 1995; Roup et al., 1992; Solomon, 1989; Warren, Rosebery, & Conant, 1989). Needed are more reports of studies that focus on the day-to-day events in the real world of classroom life. Everyday events are often left to the imagination of the classroom teacher ending in frustration from attempting inquiry-based strategies. This study serves to provide a detailed view of inquiry-based instruction in a high school science classroom.

Context of the Study

This report is part of a larger study initiated by a visit to the classroom of a high school biology teacher in a small rural town in the Pacific northwest. The school in this study is a public high school of approximately 300 students in grades 9–12. The town is a small logging town of 4000 located along either side of a highway to the Pacific coast situated near a university community of 50,000. Knowing of my research and interest in project-based instruction, a colleague encouraged me to observe this teacher. Jake, a pseudonym, had taught for 12 years and held a masters in arts in teaching degree. Jake’s professional experience prior to teaching included beekeeping. Jake’s ecology and botany courses met every other day for 90 min. This report focuses on the interactions of Jake and the 20 students in his ecology class. These students
consisted of juniors and seniors, nine of whom had requested to take ecology a second year as an advanced course.

Methods

Sources of Data

The case study of Jake and his students developed from multiple sources of data representing perspectives of the researcher, the teacher, and the students in Jake’s class. These data included four semistructured interviews of the teacher, the researcher’s journal notes of informal conversations between researcher and teacher occurring weekly, videotapes of classroom lessons and field trips, interviews of eight randomly selected students, student products, and an end-of-the-year, teacher-designed, anonymous student questionnaire. The main data of the study involved actual classroom observations captured on videotape one to two times per week during the course of the school year. The researcher served as participant-observer and captured lessons using a videocamera positioned on one side of the classroom. During these lessons the researcher was able to zoom in on various conversations between teacher and students, as opportunities presented themselves. The researcher accompanied the class on several data collecting field trips and had opportunity to interview students as well as capture group interactions. This report will focus on a subset of the data including two interviews of the teacher and interviews of six randomly selected students, researcher’s journal notes of informal conversations, written responses to the four open-ended questions on the student questionnaire, and nine videotaped lessons that occurred during September and October. Videotaped student interviews were guided by the following five general questions:

1. Can you tell me about the project you are working on?
2. What are you trying to find out?
3. Do you see any problems?
4. How has the teacher helped you?
5. What have you learned in this class?

The four questions on the teacher-designed questionnaire were

1. What are my strong points as a teacher?
2. How could I be a more effective teacher? Please be specific.
3. What do you like best?
4. What did you like least?

The nine lessons analyzed for this report contained critical incidents representative of the kinds of events occurring throughout the year that appeared to contribute towards establishing an inquiry-based learning environment. In this paper the term “critical incident” refers to a series of interactions between teacher and students eliciting actions that resemble the descriptors of inquiry-based instruction that appear in the National Science Education Standards (NRC, 1996). (See Table 1 for references.)

Analysis of the Data

An interpretive approach was used to analyze the various data sources to help answer the overall question, how does this teacher establish an inquiry-based learning environment
The extensive data collected throughout the year provided an in-depth picture of this teacher’s classroom environment. One of the challenges of a report of qualitative research is in portraying enough details of the events and actors to give the reader a sense of the complex nature of the classroom. At the same time, it is important to distill the important themes and key events, so that the reader is not swamped with details. This report will focus on nine of the early lessons related to the first two projects undertaken in the ecology class—analyzing the environmental quality of the Mary’s River and the Kiger Island Slough. Analysis of the data consisted of first reducing the data, displaying the data in matrices, and finally drawing conclusions and verifying these conclusions (Miles & Huberman, 1994). Data reduction of videotaped lessons involved creating narrative documents using a method developed in previous interpretive studies of project-based classrooms (see Crawford, 1996; Krajcik et al., 1994). The author and two graduate students divided up the lessons, and independently created these narrative documents. Analysis was guided by the research questions and the descriptors of inquiry-based instruction (see Table 1). The narrative documents included a lesson overview that described the various lesson segments and commentary related to each of the lesson segments. For example, lesson 9-9-96 consisted of five lesson segments: Segment One, Review of Homework Assignment; Segment Two, Correcting Errors in Counting Method for the SCI; Segment Three, Determining Significance of Discrepancies in the Data and Modification of the Protocol; Segment Four, Re-analyzing Macroinvertebrate Samples; and Segment Five, Discussion.
of Re-count Results. The following commentary for Segment Three illustrates the nature of this part of the data analysis.

Segment Three Commentary

During this segment the teacher raises a question about the consistency of the class data and indicates they are not interpreting yet, just looking to identify inconsistencies. As the teacher goes line by line down the data displayed on the transparency, he queries students and asks them to justify taking an average of all the counts. After several minutes of student responses, the teacher poses the questions, “what if it missed by one or two? Where do you draw the line between an accurate count and a count that is too far off?” Teacher presses students to make a decision to resample and asks for a show of hands. Some of the students appear hesitant to make a decision and only half-raise their hands. However, the teacher decides that most of the students prefer to do a re-count. The teacher admits that it may have been the teacher’s fault. “I should have been clear in my objectives for sampling for you guys.” One boy points out that problems existed with the identification of organisms that appeared too small to be seen without a magnifying glass. Students and teachers continue to discuss possible errors in recognizing live organisms versus inanimate objects such as stones. This lesson segment ends with the teacher reminding students to have their partner check their data sheet and try to get more consistent results. This part of the lesson deals with grappling with data and involves the teacher and students in an in-depth discussion of the consistency of their results. The teacher actively leads the students in carefully scrutinizing the data and goes with the one student’s suggestion to only count the specimens you can see with the naked eye. Throughout this segment the teacher actively guides students through a series of questions in looking at each data entry and questioning reliability. This relates to student understanding that is actively constructed through individual and social processes.

Following the writing of overviews and commentary, the author and graduate students transcribed all parts of lessons that related to aspects of inquiry. Finally a summary of each lesson was written. In addition to the narrative documents produced from the videotaped lessons, all student and teacher interviews were transcribed and added to the chronological data set.

Placing these narrative documents in chronological order served to highlight patterns of teacher and student actions that appeared characteristic of this classroom. Coding and interpretation consisted of reading and re-reading each narrative document, underlining sections of the transcription, and noting emerging patterns related to inquiry by writing these in the margins of the documents (Krathwohl, 1998). Bi-weekly conversations between the author and two graduate students contributed to the reliability of the assertions made by the three about Jake’s teaching. The case study developed from hypotheses and commentary written in these narrative documents (Yin, 1989). Each of the data sources (interviews, researcher’s journal notes, videotaped lessons, informal conversations, student questionnaire) were used to either corroborate or refute developing patterns and themes as these emerged from the analyses of the data. Finally, Jake was asked to react to the final assertions made about his teaching, with which he agreed, with the addition of the role of ‘modeling behaviors of a scientist.’

Results

Throughout the course of the year, Jake engaged his botany and ecology students in several teacher-created, long-term projects designed to provide data for groups in the local community: the United States Fish and Wildlife Service, a local citizens’ group concerned about river quality,
a logging company in town, a local grower of gourmet lettuces, and the nearby university. Ideas for these projects developed from Jake’s connections with outside people and agencies. The classroom projects that resulted from these connections included

1. Environmental Quality of Mary’s River
2. Environment Quality of the Kiger Island Slough
3. Designing a Constructed Wetlands that was “contracted” by a local lumber company as a wetlands mitigation plan
4. The Lettuce Project that evaluated varieties of winter lettuces for a commercial grower
5. The Forestry Project that involved students in investigating a local woodlot
6. The Independent Student Research Project (related to a variety of outside contacts).

Themes transcended these projects suggesting the importance of six key characteristics of this teacher’s inquiry-based classroom:

1. Situating instruction in authentic problems
2. Grappling with data
3. Collaboration of students and teacher
4. Connection with society
5. Teacher modeling behaviors of a scientist

My objective was to identify the kinds of strategies used by this particular teacher. I did not anticipate some of the critical incidents that contributed to the inquiry-based environment that developed in this classroom or the significance of the varied roles of the teacher. The findings of this study will be organized around the research questions, beginning with characterizing Jake’s beliefs and practices, followed by vignettes of selected critical incidents, and delineation of the roles of the teacher and students. The report concludes with implications for researchers and practitioners with a focus on how this study translates to classroom practice.

Characterizing the Teacher’s Beliefs and Practices

Jake expressed his beliefs about teaching and learning in semistructured interviews and informal conversations. Six key characteristics emerged from triangulating the varied data sources. First, Jake situated instruction in authentic problems. The authentic nature of the class projects was a recurrent theme in Jake’s description of his instruction. The use of the term authentic in this report relates to real-world kinds of activities and thought processes carried out by scientists and relevant to students’ lives. Authentic instruction involves creating environments similar to those of practitioners, yet related to adolescents (Brown, Collins, & Duguid, 1989; Resnick, 1987). In designing the projects Jake pondered the meaningfulness of these projects, the similarity to scientific work, and relevance to his students.

Basically we want to draw them into some kind of meaningful study where they’re doing something that is real... I want them to be involved in a project where they’re doing science, and they’re developing as a scientist as they go... The main thing here is that...what we have here are some students who are, and in most schools I think it is probably true, who are really capable of doing some good stuff in science, you know not fill in the blanks, or doing dry labs, or stuff like that. But doing some real research, and writing it up, and making their expertise available to certain people, like public agencies, like the
Forest Service or the National Germ Plasma Repository, or Fish and Wildlife . . . So, that’s what I am thinking right now, because it gets them into real research. (Teacher Interview, 9/11/96).

Yet, Jake admitted that his projects were more contrived than his students imagined: “this is not data that is going to shake the world.” (Teacher Interview, 9/11/96). Jake carefully considered the merits of potential projects, then designed each study, and throughout the course of instruction communicated to his students the importance of their work. When introducing the Kiger Island Slough study to the class, Jake emphasized the real-world importance of their data, as illustrated by this excerpt from a lesson in September.

During the first or second week in October we are going to be spending a whole day in the field collecting data at the Kiger Island Slough. This is a project that we have been running for two years, and this will be the first year after the flood, and Fish and Wildlife is very interested in what we come up with. (Ecology Lesson, 9/25/96).

Jake communicated to his students his own interest in the study as they began analyzing the data from the Mary’s River field trip, and the unknown results, as illustrated in this excerpt.

I don’t really know what we’re going to find out. It is really going to be interesting to get some data and to get some base line data for comparison, might give us some ideas for questions we might want to ask further, might give us some indications as to what kind of condition the river is in...I really have no idea. (Ecology Lesson, 9/13/96).

The authenticity of the river and slough studies was further highlighted by Jake’s arrangement for a professional symposium. The printed program handed to all members of the invited review panel documents the authentic nature of the event.

Thank you for making the time to support our students as they share their research with the community. We hope this format will allow for a two way exchange of information, data, and ideas between students, community members, scientists, and others committed to the long term health of our stream ecosystems. It is our hope that by providing water quality data and analysis, local politician and resource managers will be better able to justify their decision making processes. You have been invited because we value your input. We encourage you to ask questions or share your expertise during the 5 minute question and answer period after each presentation. (Symposium Program, 12/16/96).

The panel of experts consisted of school officials, including the high school principal, university scientists, university science educators, a forest historian, and reporters from the local paper who questioned and critiqued the students’ findings.

The anonymous student evaluations at the end of the year affirmed Jake’s practice of situating instruction in authentic projects and underscored the value placed on important work (pseudonyms are used for questionnaire numbers):

Carla: I liked the hands on work instead of book work, because I got more out of the class. I also tried harder because what we were doing was worthwhile and beneficial to society.

Mike: You present material in an interesting way, and use material in real life situations.

Dawn: I liked all the field work. I liked how I could see how the stuff we learned is awfully important. I liked even when you were in pain with your back, you still had a positive attitude and gave us your best. (Questionnaire, 6/5/97).
By the end of the year the students’ reflections of their ecology work correlated with Jake’s goals and objectives stated in the beginning of the year. Almost all students wrote they liked the field work best, and in particular, the river and slough study, and valued the authentic nature of the projects.

Second, Jake promoted the importance of grappling with data. Jake believed it was important to guide students in carefully collecting and analyzing real-world data, and to maintain high standards for student work. “They’ve got to be real meticulous about what they’re doing out there.” Jake pressed his students towards rigor in interpreting the data. Student interviews verified the importance Jake placed on grappling with data and trying to make sense of it as illustrated by this student’s comment:

Heidi: And so me and Wilma (pointing over her shoulder at Wilma who was working at a computer) are working on the riparian vegetation, and what we’re going to do is to take the three different graphs, and find the biodiversity, and then put the three graphs together—maybe lay them on top of each other, and see like with bar graphs and line graphs how they differ. (Interview, 10/26/96).

In fact, two students commented that Jake's high expectations had a negative impact on them. In responding to the question, what do you like least about the class, these students wrote

Pete: The high expectation of the work quality. However, I am glad it taught me to do quality work, so I guess that it was good.

Jerry: Our independent research project in conjunction with the wetlands project. It’s just too much to do. Also, your grading is wacko. We are 16–18 year olds. We’re NOT in college yet!! You could be a little more forgiving, after all the work that goes into things. Slow down once in a while and listen harder. You are hard to pin down. You also have incredible expectations. We’d all like to succeed, but we are spread very thin. (Questionnaire, 6/5/97).

However, the majority of the students valued the rigor expected of them as evidenced by this representative response, “I like how you challenged every (one) to think for themselves and liked how you were tough, but fair to everyone” (Student #13). This theme of ‘grappling with data’ will be further illustrated through vignettes of critical incidents later in this paper.

Third, Jake fostered collaboration of students and teacher. Jake constantly gave his students encouragement, and he considered them valued members of the classroom research team with himself as collaborator and research director. “You all did well in biology. Most of us have taken more science than is recommended. We have a high powered group of data collectors and interpreters.” (Videotaped Ecology Lesson, 10/1/96).

During one of the lessons prior to the important data collecting trip, Jake delegated the responsibility for organizing the groups to the second year students, “You veterans will go back in my office and you will plan the field trip for next Wednesday.” (Videotaped Ecology Lesson, 10/1/96). Students felt valued as contributing members of the research team as shown in these student comments:

Ben: You have too many to list, but I will start off by saying you listen to our ideas really well, you are open to new ideas, you care about how we do…

Rebecca: Giving the students a chance to pursue their interest in their specific area… is very positive all the time. (Questionnaire, 6/5/97).
Student interviews highlighted the collaborative nature of the classroom, the students’ perception of their importance as contributing members, and the collaborative orientation of the teacher. Hanna’s statement represents the views of all the students:

Hanna: We are all trying to find out different things, pretty much. But the main thing is, after they’re all combined, we’re going to try to figure out if the flood affected the water quality, and that’s why we need to figure out the invertes and all that, because they determine how polluted the water is. . . . He gives us lots of examples and stuff like that. (Interview, 10/26/96).

Fourth, in initiating and carrying out projects, Jake connected students with the community. Students acknowledged the connection of their science instruction to their community, as illustrated by this student’s written comments:

Eileen: You are very enthusiastic and have tons of good ideas—also a lot of good contacts. Also you make things interesting and get us involved in projects that actually will help out the environment close to us. You get us in good habits as in actually doing something about our problems environmentally in our community. (Questionnaire, 6/5/97).

In response to the question, what was best about the ecology class?, this student’s remark was typical: “The real life situations. Involvement in the community. I think the way you teach the class is fine. Do not change anything.” (Mike, Questionnaire, 6/5/97). The most common suggestions for how Jake could become more effective included slowing down the pace and reducing the number of long term projects. The following three students’ responses illustrate some students’ discomfort with the pace and complexity of the work:

Rachel: I thought that many assignments weren’t explained clearly enough and many of the out-doors hands on projects seemed rushed. It would have been more enjoyable and educational if we had had more time on certain projects.

Ben: I think you would be more effective if we didn’t skip around so much. For example, when we were doing our I.D., we seemed to be doing too many things at once.

Vince: Well, I personally think you got involved in too much this year. It was a whirlwind. I didn’t feel like I had enough time to actually do a good job on my projects. Also we had too many projects going on at the same time. Maybe scaling it down a bit would be more effective. (Questionnaire, 6/5/97).

It appears from these responses that the negative aspect of the community-based projects stemmed from the number and complexity of the projects, the overlapping time frames of projects, and the extended time required for each project. Yet, the responses to other questions clearly indicated that the vast majority of the students valued the connection of the projects with their community and with society.

Fifth, Jake modeled behaviors of a scientist. As Jake worked with students in the classroom and field in designing the studies, collecting data, analyzing the data, and sharing results with the world outside the classroom, his actions modeled the work of scientists. This characteristic of Jake’s instruction was articulated by Jake after reading a draft of this report. Many examples from the videotaped lessons point to Jake modeling the following behaviors: connecting studies to previous research, attention to careful sampling techniques, taking replicate samples, questioning data that appeared inconsistent with other results, and asking more questions as the
study progressed. Student’s perceptions of their teacher’s actions is illustrated by Hannah’s statement:

Hannah: And another thing that really helps is he gets down there and he does it with us. You know, he was in his hip waders when we went down there (in the slough), sifting through the invertes with us, and that really helps us to concentrate, and see how important it really is. (Interview, 10/26/96).

Modeling scientists’ behaviors is illustrated by Jake’s “hip-wader” style of working with students in which he “gets down there and he does it with us.” Jake did not hesitate to immerse himself in collecting and grappling with data, shoulder to shoulder with his students.

Sixth, Jake fostered ownership by students. For three weeks in October and November Jake was absent due to back surgery. During this time students worked in the computer room, essentially self-directed in writing up their final team reports of the Mary’s River Study and the Kiger Island Slough. During interviews students articulated an understanding of the purpose of the water quality studies, the ecological nature of rivers and sloughs, and a belief that their study had significance for outside agencies:

Leah: We’re doing a comparative study of Kiger Island Slough, which is just a slough outside of Central City, and it’s important because right now, the river’s been channeled, and so there’s not as many of the sloughs that people think. They don’t have enough, like, data, but they think they (sloughs) can filter out some of the pollutants that go into the river. So, we feel our study is important because it was the first one done on one of the sloughs. And, so, this year, we had a flood last year. . ., so this year we’re doing a comparative of the last two years of data. So this year is three years of compiling data. (Interview, 10/24/96).

Jake’s week’s absence during the critical time of analyzing the data, finalizing conclusions, and writing up technical reports could have stalled students’ momentum and contributed to inability of groups to complete their research reports. On the contrary, the substitute teacher reported that students worked collaboratively in the computer room led by the second year students, as evidenced by these student statements:

Leah: We’re just, he’s not here right now, so we’re just kind of doing it. We just figured out what needed to be done. We have to compare everything, like the aquatic vegetation, the riparian, everything. And then, how we’re going to do it. Which is like, we have to get a standard for all of us. (Interview, 10/24/96).

The authentic nature of the projects and their unknown results, in contrast to traditional laboratory exercises, motivated the students as shown by Heidi’s comments:

Researcher: Do you think this is an important study?

Heidi: Yeah, I do (nodding). It’s, I think it will be really important because, I mean, I’m personally, I just won’t know if the flood did change everything, you know, and I’m kind of anxious to see the results . . . if it did (change). (Interview, 10/24/96).

The ownership by the students was demonstrated by one boy’s reluctance to be interviewed until his team had compiled and analyzed most of the data. When Brian finally agreed to be interviewed, he articulated a sincere interest in the work of the ecology class.
Researcher: So what kinds of questions are you asking?

Brian: Well, I have been pretty involved in the aquatic vegetation data. You know, right from the... I, I worked with it in the slough, and then I've been typing it up and everything (looking over at the computer monitor.) And we've noticed some pretty significant changes, actually. Especially... there’s... there’s a species of Elodea that’s invasive. And, it seems to be taking over the aquatic vegetation. So that is kind of an interesting thing. (Interview, 11/18/96).

Later in the interview, this same boy indicated that he viewed the various parts of the projects as important to his future college studies.

Brian: I’ve learned an amazing amount in this class. I mean, you know, it is hard to detail down on a few things. Um, ah, let’s see. Well, first of all, I know how to write a research paper. That is a really important part of scientific research... anything in the science field. And so, um, I have been looking around for colleges, and stuff, and they are talking about how, you know, 'our students have to do a research paper for the first time', and so I think this is a really important part of this class. ...This is like the only class where we like go out on these field trips and swim around in sloughs and look at, you know, invertebrates and stuff, and I think that’s great. You know, other classes, you know, you sit down and listen to a lecture... It is definitely my best class. (Interview, 11/18/96).

The six key characteristics of Jake’s ecology classroom (situating instruction in authentic problems; grappling with data; collaboration of students and teacher; connection with society; teacher modeling behaviors of a scientist, and fostering student ownership) became apparent during critical incidents during the course of the instruction.

Critical incidents That Contributed to This Inquiry-Based Classroom

During the course of Jake’s instruction, events occurred that significantly contributed to this inquiry-based environment. These events, referred to as “critical incidents”, were points during the course of a project that demanded an immediate decision by Jake, as to how to proceed. Jake’s actions during these critical incidents communicated to his students important aspects of scientific inquiry. Examples of critical incidents during the first two months are summarized in Table 2. One critical incident related to an anomaly found in the class was that bacterial data that resulted in Jake orchestrating a lengthy interactive discussion about what to do about it. This critical incident occurred during the lesson following data collection on the Mary’s River. At the beginning of class Jake had posed the question, did they perhaps sacrifice accuracy in their data collection due to limited time in their attempts to sample at two sites versus one? “My biggest concern was, and I want to get your opinion on this... we wanted to get a lot of data in a short period of time. Do you think we牺牲ed uh, quality or the time that we had. In other words, were we rushed so much that you questioned the data we may have got?” When compiling the class data on the overhead, Jake pointed out that one of the bacterial counts was extremely high at one of the sites. One of the girls had notified Jake earlier that a loose cap on her collection bottle might be a source of contamination. Over the next 25 minutes Jake guided students’ thinking through extensive questioning. Jake’s students eventually suggested that the reliability of the data would be enhanced by subsequent sampling of the site. As was characteristic of Jake’s instruction, students’ opinions were frequently solicited. This vignette of a critical incident illustrates the characteristics of situating instruction in authentic problems; grappling with data, collaboration of students and teacher, and teacher modeling behaviors of a scientist).
Table 2
Vignettes of selected critical incidents and the teacher’s decision about subsequent instruction

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<tr>
<th>Critical Incident</th>
<th>Teacher and Student Actions</th>
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<tr>
<td>Anomaly in the data</td>
<td>Extended time spent in class discussion&lt;br&gt;Teacher spent 25 minutes in leading students through questioning techniques in critiquing the bacterial count data. When asked if they should throw out the high count, one student suggested putting an asterisk by it. Teacher agreed that throwing out the high count might skew the results. A student suggested that they resample the site. Teacher agreed, “that’s the whole idea, of science and replication.” A second student suggested, you need five replications to be statistically significant. (situating instruction in authentic problems; grappling with data, collaboration of students and teacher, and teacher modeling behaviors of a scientist)</td>
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<td>Bacterial counts were made of the two samples sites on the Mary’s River and recorded on the overhead. However, one of the bacterial counts was extremely high, compared with the other counts. One girl informed teacher that she suspected contamination due to a loose lid. This incident was preceded by the teacher commenting. “When you put data up there and something doesn’t make sense, we try to question that because we don’t want to be analyzing data that was inadequately taken or inadequately reported or transferred, or whatever.</td>
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<td>High bacterial counts in local river</td>
<td>Teacher poses social responsibility question to students&lt;br&gt;Teacher decided to continue discussing the issue of potentially high bacterial counts. Teacher posed the question to students, do they feel responsible for informing people who might swim at the local park, of the possible high bacterial counts at this site on the Mary’s River? Teacher led a discussion resulting in students’ suggesting that they collect additional samples. Teacher asked if students were willing to collect the samples, and many volunteered. (situating instruction in authentic problems; collaboration of students and teacher; connection with society; and development of student ownership)</td>
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<td>A newspaper article focused a class discussion of polluted streams and rivers. Teacher returned to the discussion initiated during a previous lesson. Class data recorded during the previous lesson had indicated potentially high bacterial counts in the Mary’s River.</td>
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<tr>
<td>Discrepancies in invertebrate diversity test</td>
<td>Students suggest a standard protocol and request to re-analyze the invertebrate data&lt;br&gt;Through a lengthy class discussion, the teacher and students realized that the problem in data consistency may have resulted from a problem in differentiating tiny living from nonliving things in the samples. Students settled on a standard protocol, and decided to postpone analysis of Sample #2 and reanalyze Sample #1. Discussion and reanalysis took a total of 55 minutes. (grappling with data, collaboration of students and teacher, and teacher modeling behaviors of a scientist)</td>
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<tr>
<td>Class discovered discrepancies in consistency of total counts of organisms during a teacher-led discussion focused on scrutinizing the invertebrate data from Mary’s River Sample #1.</td>
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Another critical incident related to the class finding a moderately high count of coliform bacteria at one of the sites, and the real possibility that this situation posed a danger to children swimming in the river. Jake decided to bring up the issue again following the session of the initial data analysis, and asked students what their responsibility was in informing the community. At the beginning of the class Jake read a newspaper article from the local newspaper to connect scientific data with community decisions on environmental issues. Jake ended the discussion of the news article with, “You are probably getting the feel that ecology and biology isn’t just doing science. Lots of times you are getting into public policy. And what I wanted to ask you guys is, have you mulled it over? Have you thought about the data we got at Mary’s River Park, where a lot of kids go swimming in the summer?” Although led by their teacher to consider notifying health department, students seemed unsure about the reliability of their data, and were reluctant to go the next step. Instead, students suggested that more samples be obtained. When Jake asked who would be interested in collecting these additional samples outside of school time, more than enough students volunteered. During this critical incident these characteristics were evident: situating instruction in authentic problems; collaboration of students and teacher; connection with society; and development of student ownership.

A third example of a critical incident emerged when students got different total counts of organisms while doing a test for biodiversity. An interactive class discussion resulted in students suggesting a modification in the protocol. Students made a consensual decision to go back and reanalyze the sample data. This incident consisted of another extended whole class discussion of possible discrepancies in data analyses. In this case, the discrepancy resulted from how students looked at the invertebrates. The sequential comparison index for invertebrates (SCI) involved calculating a ratio of the number of runs of the same kind of organism to the total number of invertebrates in a sample. Students counted grid squares that had different species and indicated a run ended when the kind of organism in the next square changed. Students checked their partner’s analysis, after first stirring up the sample. A problem emerged when the total number of organisms differed in two checks of a single sample. The test depended on students’ ability to differentiate tiny organisms from inanimate things. Jake had never used this test before, and he admitted to students, “Maybe this is my fault. We are having people find sometimes more or less organisms than the people that counted before them. Now what could that be attributed to?” This excerpt illustrates the interactive nature of the discussion, and Jake’s modeling of how to critically look at the data.

Teacher: O.K. Well, let’s go down here (pointing to the data on the overhead). We got 76, 72, number of organisms . . . there’s just one different there. Here we got 63, 77 . . . number of organisms is 27 and 31, so four different. And what I am thinking is that when you get those differences, maybe you got people who are carefully looking and counting all organisms, and maybe, you got people counting things that are not easy to see, really, and not maybe. What’s that?

Wayne: Maybe they are counting rocks.

Teacher: Counting rocks? Wayne, are you counting rocks again (joking to the student). Yeah, that’s a difference that might be worth checking. Here we got 50 and .6, a little different numbers of organisms there. Yeah. 38 and 38...that is the type of data I would like to see. Because, ah, we do have a difference in runs, which is a reflection of what?

Students: in chorus: Randomness.
After the students made the decision to reanalyze the first sample instead of moving on to the next sample, Jake led a class discussion centered on establishing the protocol for the test.

Teacher: O.K. What should we be measuring down to, you guys? Are we going to say, everything you can see down to a naked eye. Or, are we going to use magnifying glasses? Or, are we going down to a hand lens?, or..

Susan: one girl interrupts. What you can see with a naked eye, that you can tell is an invertebrate. I mean, you can see if it is a snail. And, you can see if it is a worm.

Teacher: All right. Susan says down to the naked eye.

Tom: What if you see something that you think is alive?

Susan: That’s fine.

Tom: If you can still see it with the naked eye.

Teacher: O.K. Here’s one way you can deal with that. If you can tell it is an organism and not a pebble, count it. If you want to find out if it is the same as the other one or not, and you can’t tell, use a magnifying glass to find out if it is the same or different from the one that you had. But don’t go looking for specimens that way. Does that make sense?

Jake instructed the students to take out the samples again and asked if there were any additional considerations.

Tom: Pouring them back and forth.

Teacher: Tom’s concerned with keeping our organisms in good enough shape to identify them again because we have to do two more tests on these things that we will have to be able to tell what they are . . . . Tom, are yours looking bad?

Tom: I got a few legs floating around.

Teacher: A few legs floating around? That could be from our methods, or from the sampling. O.K. people, remember to do a data sheet, and do your runs over organisms, and pass your data sheet for somebody else to check ’em, and let’s try to get some more consistent stuff here.

During the next lesson, Jake complimented the students for not settling for “funky data”, and stated he thought their data was now within the range of randomness. Jake reminded students that this process was important if “we are going to keep up our reputation as a research organization.” During this critical incident these characteristics were evident: grappling with data, collaboration of students and teacher, and teacher modeling behaviors of a scientist.

These lesson excerpts represent the kind of extensive questioning used by Jake throughout his instruction, both in large and small group settings. Jake’s general strategy for teaching students how scientists grapple with data consisted of modeling ways of critically looking at data. Similar to Jake’s field-work style of getting on his hip waders and getting down to ground level with the students, Jake constantly used this same kind of “down and dirty” approach when working with students on a cognitive level.
Roles of the Teacher and the Students

The first part of this report described the characteristics of Jake’s instruction through his words in interviews, reflections of his students, and from the discourse during critical incidents during instruction. From these data emerged roles that Jake assumed, and roles that his students assumed. In this inquiry-based classroom the roles of the teacher changed with the change in tasks. Osbourne and Freyberg (1983) suggested varied roles for teachers using constructivist approaches to teach children about science. These roles included those of motivator, diagnostician, guide, innovator, experimenter, and researcher. Jake adopted these same roles at various times. However, Jake took on additional roles that implied an even more complex look at what it means to be a teacher in an inquiry-based classroom. The ten roles that Jake assumed and evidence from the data included the following:

1. The role of motivator involves the teacher encouraging students to take responsibility for their own learning. When describing his teaching Jake stated that, “we try to build them up all the time, and say, you know, you guys are sharp people, and we’re depending on you to do this accurately and well, so what do we need to think about here when we’re designing this?” Jake’s students acknowledged their teacher’s role of motivator as illustrated by these written comments: “You enjoy teaching ecology and this is very apparent when you teach. Your enthusiasm is contagious”; and “I liked the fact that you are interested in what you teach and your enthusiasm rubs off on us.”

2. The role of diagnostician involves the teacher giving students opportunity to express ideas in order to discern their understandings. Evidence from Jake’s teaching illustrating his role of diagnostician includes this description: In the beginning of a lesson after the Mary’s River field trip Jake asked students, “Would you write down a paragraph, sort of reflection, on the experience. It could be scientific, the feeling you got, ecologically. It could also be related to how the class worked.” In describing the lettuce project Jake stated, “I mean, I am always evaluating them out there (in the garden) trying to ask them questions when they’re doing things, asking them what they are doing it, and why they are doing it.”

3. The role of guide involves the teacher directing students and helping them develop strategies. This incident illustrates Jake’s role as guide: During analysis of the Mary’s River samples, Jake led students in critiquing the bacterial counts. When asked if they should throw out the high count, one student suggested putting an asterisk by it. Jake agreed that throwing out the high count might skew the results. Then Jake continued his guidance with a follow-up question.

4. The role of innovator involves the teacher designing instruction by using new ideas. Evidence of Jake taking the role of innovator includes this example from his philosophy statement. “Basically we want to draw them into some kind of meaningful study where they’re doing something that is real . . . I want them to be involved in a project where they’re doing science, and they’re developing as a scientist as they go.” Jake’s students’ perceptions of the impact of Jake’s ideas on instruction are represented by this student’s statement. Karen stated, “There’re so many new things coming up, and he’s always passing them out to us. He’s always informed, and going to meetings and whatever.”

5. The role of experimenter involves the teacher trying out new ways to teach and assess students. This statement illustrates Jake’s role as experimenter. During an interview Jake explained that he had questioned the owner of the gourmet lettuce farm on how they determined the best varieties for production. Jake developed the idea to have his students involved in testing different lettuce varieties. Jake stated, “I thought that maybe we ought to try that too, and have the kids actually evaluate them.”
6. The role of researcher involves the teacher evaluating his or her own teaching and engaging in solving problems. Evidence from the data of Jake taking the role of researcher includes the following: Jake frequently asked his students for feedback on his instruction, both in writing and during individual and group conversations. In this way Jake researched his own teaching and modified his teaching as he received feedback.

7. The role of modeler involves the teacher showing the attitudes and attributes of scientists by example. This particular role is one identified by Jake. Examples from his teaching confirmed adopting this role. Following is an example: During a lesson prior to the data collection field trip to Kiger Island, Jake stated: “It is really going to be interesting to get some data and to get some base line data for comparison, might give us some ideas for questions we might want to ask further, might give us some indications as to what kind of condition the river is in...I really have no idea. I don’t really know what we’re going to find out.” Students confirmed Jake’s role as modeler as illustrated by this written statement from the questionnaire: “I liked it even when you were in pain with your back, you still had a positive attitude and gave us your best.”

8. The role of mentor involves the teacher-supporting students in learning about scientific work. Evidence from students’ questionnaires revealed that they viewed their teacher as knowledgeable and capable. For example, one student wrote, “You are there to help us when we need it. And try to give us work to make us think and do well.” Another student stated during an interview, “Mr. M. obviously knows what he is doing, and so that helps. So if we have a question, we can ask him, and if he doesn’t know the answer, you know, he’ll tell us where we can go...he has a lot of background on a lot of different subjects.”

9. The role of collaborator involves the teacher and students exchanging ideas, and allowing students to take on the role of teacher. An example of Jake’s relinquishing his role as director of instruction is illustrated by this incident: During one of the pre-Kiger Island lessons, Jake delegated the responsibility for organizing the important data collection trip to the second year students. “You veterans will go back in my office and you will plan the field trip for next Wednesday.”

10. The role of learner involves the teacher opening oneself to learning new concepts. Students in Jake’s class recognized his openness to learning new ideas and taking the role of learner. An example of students’ views of their teacher as learner is illustrated by this written comment from one of the student questionnaires: “You are like a student yourself, always curious and wanting to learn.”

The additional roles adopted by Jake of modeler, mentor, collaborator, and learner may appear to overlap the original roles for teachers using constructivist approaches to teach children about science as articulated by Osbourne and Freyberg (1983). The point I am stressing is that teacher’s work in an inquiry-based classroom requires taking on a myriad of roles—roles that demand a high level of expertise.

The students in this ecology class took on varied roles that emerged from Jake situating instruction in authentic problems and from his endeavors to have students do work similar to that of scientists. At times these roles resembled those of students in traditional, information-driven classroom, such as learner, listener, and receiver of information. More often, Jake’s students took on roles generally not taken on by students in traditional, topic-centered classrooms. These new roles included active collaborator, leader, apprentice, teacher, and planner. In other words, some roles assumed by students in this high school ecology class included those roles usually reserved for the teacher.
Discussion

The motivation for this study centered on the need to close the gap between research and practice by developing a useful model of inquiry-based instruction. Missing from many narratives of inquiry-based classrooms are the details of the student–teacher interactions during the course of long-term projects, from start-up to the final student reports. Other missing details include the beliefs and pedagogies of teachers who appear successful in engaging students in the kinds of inquiry-based lessons portrayed in the standards. Needed are the voices of the teacher and students, which are vital to developing understanding of the nature of an inquiry-based classroom. Teachers striving to change their pedagogy to include strategies that teach students about scientific inquiry through ill-structured projects may lack knowledge of the processes involved. Ill-structured projects include those that do not follow explicit steps. As noted in Rosenshine and Stevens’s summary of the research on teaching functions, explicit teaching functions relate best to well-structured subjects and not to open-ended projects (Rosenshine & Stevens, 1986).

This study suggests a complex model of inquiry-based teaching that I term, collaborative inquiry. The collaborative component of this instruction involves cognitive interactions between teacher and students with members of the community. The collaborative interactions resemble those of the participants in a legitimate peripheral participation (Lave & Wenger, 1991). Collaborative inquiry involves the creation of a classroom learning environment that highlights new roles for teachers and students. These roles differ from the traditional roles of teacher as knowledge-giver and student as knowledge-receiver. Instead of a teacher-centered model, the teacher and students collaborate to develop conceptual understandings through shared learning experiences. This model embraces the six characteristics of Jake’s ecology class

1. Instruction situated in authentic problems
2. Focus on grappling with data
3. Collaboration of students and teacher
4. Connections with society
5. Teacher modeling behaviors of a scientist

An important theme in Jake’s classroom involved the authentic nature of the students’ work. The authenticity of the work was reflected by the students’ persistence in working up the data and their beliefs that their work was important. The ownership the students gained through the projects confirms reports of other experienced teachers involving their students in student-centered projects (Crawford, 1996; Roth, 1995; Roup et al., 1992; Scott, 1994; Warren, Rosebery, & Conant, 1989).

The initial question of this study, how does this teacher create a classroom environment in which students appear self-directed and engaged in scientific inquiry?, was precipitated by a videoclip look at Jake’s classroom the previous year. Although this case study involves one setting, one teacher, and one school, assertions about Jake’s teaching may enable researchers and teachers to sharpen our focus when looking at what it means to teach about scientific inquiry in school classrooms. These assertions include (a) inquiry is situated in a context, (b) teachers need to embrace inquiry as a content and pedagogy, (c) collaboration between teacher and students enhances inquiry, (d) teacher and student roles are complex and changing, (e) greater levels of involvement are required by teachers than in traditional teaching.

This study suggests new roles for teachers that are more demanding than have been commonly depicted. Common descriptors of roles for teachers using constructivist and inquiry-
oriented approaches include “teacher as facilitator” and “teacher as guide.” Researchers may oversimplify the problem by contrasting only two kinds of roles, “teachers-as-knowledge-transmitters” and “teachers-as-facilitators” (Fradd & Lee, 1999). However, this study suggests a more expansive range of teacher roles necessitating more active and complex participation than that of a facilitator or guide. In this study Jake carefully conceived and developed the initial question of each project, gathered resource materials, orchestrated the instruction, mentored students in designing data collection plans, guided them in carefully collecting data, modeled for them how to systematically analyze and grapple with the data, encouraged them to ask questions and draw initial inferences, monitored and critiqued the writing-up of scientific reports, and finally, coordinated a final presentation of students’ findings to review-boards composed of scientists and citizens. Throughout the many weeks of the Kiger Island Slough investigation, Jake sustained students’ interest and reinforced the importance of grappling with data and presenting findings backed by evidence. Jake constantly pressed students about the importance of validity and reliability, and he coached students when they presented final conclusions to outside agencies and citizens groups.

Teaching students, science as inquiry (AAAS, 1993), involves engaging students in the kinds of cognitive processes used by scientists when asking questions, making hypotheses, designing investigations, grappling with data, drawing inferences, redesigning investigations, and building theories and revising theories. This kind of instruction demands a significant shift in what the teacher is doing. If asked to place the level of teacher-involvement on a continuum from least involvement to greatest involvement, many educators would place discovery learning at one end of the spectrum and traditional or explicit teaching at the other extreme. Where would one place inquiry-based teaching? One might expect to place inquiry-based teaching somewhere in the middle of the continuum. On a scale of one to ten, with traditional instruction at ten, some science educators might place inquiry-based instruction at the five position. Others would place inquiry-based teaching nearer the discovery end of the continuum, suggesting that inquiry-based instruction resembles open, unconstrained exploration by students with limited involvement of the teacher. However, I propose a very different position—placing inquiry-based instruction far to the right of traditional teaching, thus positioning discovery and inquiry-based at the two extremes of the continuum (see Figure 1).

It is important to point out the danger of simplifying a comparison between instructional modes by using a linear continuum. I am not implying that in inquiry-based teaching, the teacher does not move frequently back and forth along this continuum. Nor do I believe that inquiry consists of a set of discrete skills. In order for students to understand the nature of scientific inquiry, they need a holistic experience, not a step by step, reductionist approach like the linear steps of explicit teaching models.

Significance of the Study

What implications can a study of a single high school teacher have for researchers and practitioners? The significance of this study includes providing a more detailed view of the day-

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<th>Discovery</th>
<th>Traditional</th>
<th>Inquiry-based</th>
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<td>least</td>
<td>greater</td>
<td>greatest</td>
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**Figure 1.** Level of teacher involvement required in different instructional modes.
to-day processes involved in creating and sustaining an inquiry-based classroom. Unlike the physics classroom in which the teacher and students were worlds apart (Roth et al., 1999), in Jake’s classroom his students valued the contextualized instruction and articulated perceptions aligned with Jake’s beliefs and goals. When carefully analyzing the events and key players interacting in this classroom, the data suggests a model of collaborative inquiry that requires the teacher to take on more active and demanding roles than traditionally depicted. This mode of instruction involves the teacher modeling the work of scientists. Questions that arise from this study include

1. Do the characteristics of this teacher’s classroom translate to other scientific areas, schools, and grade levels?
2. Do strategies successful in advanced science classrooms work with all students including less advanced students?
3. How can teacher educators facilitate less experienced teachers including prospective and first-year teachers in adopting these complex roles?

This study suggests a myriad of constantly changing teacher roles that demands more active and complex participation than that suggested by the commonly used metaphor, teacher as facilitator. If we are to avoid the failures of our past related to giving teachers teacher-proof curriculum, we need to turn our attention to how best to support teachers in embracing the essence of inquiry.

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References


