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Recognizing Students' Scientific Reasoning: A Tool for Categorizing Complexity of Reasoning During Teaching by Inquiry

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Abstract

Teaching by inquiry is touted for its potential to encourage students to reason scientifically. Yet, even when inquiry teaching is practiced, complexity of students' reasoning may be limited or unbalanced. We describe an analytic tool for recognizing when students are engaged in complex reasoning during inquiry teaching. Using classrooms that represented “best case scenarios” for inquiry teaching, we adapted and applied a matrix to categorize the complexity of students' reasoning. Our results revealed points when students' reasoning was quite complex and occasions when their reasoning was limited by the curriculum, instructional choices, or students' unprompted prescription. We propose that teachers use the matrix as a springboard for reflection and discussion that takes a sustained, critical view of inquiry teaching practice.

Keywords

Teaching by inquiry; Reasoning; High school; Biology; Experimentation

Introduction

Emphasis on teaching science by inquiry dates back to the mid-nineteenth century, although its meaning has evolved, particularly during the last three decades (DeBoer 2006). Publications from the National Research Council (NRC) (1996, 2000) and *Project 2061* of the American Association for the Advancement of Science (1990, 1993) have promoted teaching by inquiry to foster student understanding of science and “encourage and model the skills of scientific inquiry” (NRC 1996, p. 32). Many stakeholders, including teachers, scientists, and science and education policymakers, promote teaching by inquiry for its potential to enhance students' development of reasoning skills. The NRC recommends that students engage in cognitive processes that typify scientists' thinking: “asking scientifically oriented questions, giving priority to evidence in responding to questions, formulating explanations from evidence, connecting explanations to scientific knowledge, and communicating and justifying explanations” (2000, p. 23), and that teachers use student data, self-reflection, and collegial discussion to determine whether instructional approaches “evoke the [desired] level of reasoning” (1996, p. 42).

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Yet, inquiry teaching is not prevalent (Etheredge and Rudnitsky 2003; Hofstein and Lunetta 2004). Tools and support for encouraging reflection and discussion about teaching by inquiry are not widely available (Davis 2002; Trautmann and MaKinster 2005) and learning to teach by inquiry continues to be a substantial challenge for preservice and practicing teachers alike (Anderson 2002; Blanchard et al. 2009; Crawford 2007; Flick 1997; Newman et al. 2004; Roth et al. 1998; Windschitl 2003). Teachers' preparedness to teach by inquiry is influenced by their knowledge about science and its methods and nature, as well as how to do science and how to go about teaching science using inquiry (Crawford 1999, 2007; Driver et al. 2000; Roehrig and Luft 2004; Roth et al. 1998; Shulman 1986). Teachers' beliefs about the nature of science, pedagogy, schools, and student learning also constrain their practice of inquiry instruction (Crawford 2007; Wallace and Kang 2004). Teachers may view factual knowledge as the most important student outcomes (Cronin-Jones 1991) or prioritize transmitting facts even when they profess an interest in teaching by inquiry (Tobin and McRobbie 1996). Teachers may be discouraged by students' resistance to assuming new responsibilities and discursive roles that are required during inquiry or by students' discomfort with inquiry's unpredictability and open-endedness (Loughran 1994; Yerrick 2000). Even in scenarios where inquiry teaching is practiced, teachers may struggle to engage students in complex reasoning (Driver et al. 2000; Singer et al. 2000). Students may spend their time collecting data or completing procedures rather than discussing data analysis, generating conclusions, or synthesizing new findings with previous ideas (Kuhn 1993; Moss et al. 1998; Watson et al. 2004). Even when teachers dedicate time to discussion, talk may focus on procedures or facts without supporting rationales or substantive discussion (Jimenez-Aleixandre et al. 2000; Park and Pak 1997).

Teachers need support in recognizing gaps in student reasoning during teaching by inquiry as a first step to mitigating them. The focus of this study is the description and application of an analytic tool for recognizing when students are engaging in complex reasoning during teaching by inquiry. To demonstrate how such a tool could be used, we set out to identify classrooms engaged in scientific inquiry in which factors that typically hindered the practice of inquiry teaching would have little impact. In other words, we sought classrooms that represented “best case scenarios” for inquiry teaching because of supportive classroom, school, and community environments. We took a case study approach to document the practice of inquiry in two teachers' high school biology classes that we identified as best case scenarios. We adapted a matrix for evaluating the complexity of scientific reasoning during inquiry in these best case scenarios and used it to categorize the (a) inquiry context for its potential to engage students in complex reasoning and (b) inquiry practice for the actual engagement of students in reasoning.

Programmatic Context

Our study centers on the practice of inquiry teaching within the context of the Partnership for Research and Education in Plants (*PREP*), an outreach program at a state university that aims to involve students and teachers in scientific inquiry that is of interest to both the education and science communities (i.e., the program has both learning and science research objectives). Specifically, teachers and scientists mentor students in designing and conducting original experiments with unknown outcomes to yield insights into the function(s) of genes that scientists are studying in the plant, *Arabidopsis thaliana*, which is investigated widely in plant biology. Students address the as yet unanswered question of whether the gene they are studying plays a role in the plant's response to environmental stresses (e.g., drought, soil pH, etc.) by comparing the growth of plants of different genotypes in stress conditions. This large-scale, systematic study to determine the functions of all of the genes in *Arabidopsis* is being funded primarily by the National Science Foundation (2008) through its 2010 Project. Thus, students have the opportunity to make discoveries that relate to the work of their scientist partner and the broader scientific community while they learn concepts in genetics, plant biology, and environmental science as well as the processes and nature of science.

Although *PREP* as an inquiry teaching context is described in more detail elsewhere (Dolan et al. 2008), it is described briefly here to provide context for the study. *PREP* starts with a dialogue in the classroom, during which project staff explains to the students that their assistance is needed in characterizing the functions of genes in the plant, *Arabidopsis*. Students are familiar with the idea that genes help determine characteristics, but usually only visible characteristics such as height or color. Students are challenged to generate ideas about why a plant with a disabled gene may look completely normal. Students are introduced to the idea that phenotypes may be revealed through the interplay of genes and environment, such that the impact of disabling a gene may be observable only when the plant must respond to changes in its surroundings. Students consider environmental factors that may influence a plant's growth and are challenged to design and conduct their own 8-week long experiments to compare how mutant plants (i.e., plants with a gene disabled) differ from their wild-type counterparts (i.e., no disabled genes) in their response to an environmental change. Students end by sharing their results and conclusions with their partner scientists, who ask questions about their findings and explain their interpretations of how the students' results fit into what is known in the field.

Theoretical Framework

Situated cognition theory frames this study because we explored the reasoning behaviors of individual learners in complex, social, and situated environments (Greeno 1997): the *PREP* curriculum and particular classrooms as best case scenarios for inquiry. *PREP* integrates students' activities into the scientists' ongoing scientific practice and provides a rich, authentic problem space for students' learning (Dolan et al. 2007; Turvey and Shaw 1995) while putting students in charge of identifying, at least in part, the focus and purpose of their investigations (Rahm et al. 2003; Roth et al. 2008). As proposed by Brown et al. (1989), the inquiry involves students and teachers in the “ordinary practices of the culture” (p. 34) by using biological materials that are being generated and studied actively by the scientific community and by engaging in back-and-forth exchanges with scientist-collaborators. Students' findings are being incorporated into science publications (Owens et al. 2008) and as preliminary results in grant proposals. As such, students and teachers are legitimate peripheral participants (Lave and Wenger 1991) in their partner scientists' current research.

In addition, the program is epistemologically authentic as defined by Chinn and Malhotra (2002), who take a cognitive approach to analyzing curricular materials for opportunities for epistemologically authentic science learning. We anticipated that this context would “indexicalize” students' reasoning (Brown et al. 1989) by enhancing or even altering the meaning of the cognitive processes employed during scientific inquiry. In other words, we were most interested in examining students' reasoning in a context that would encourage students' construction of epistemologically authentic meanings for the cognitive processes of science.

Given the many impediments to teaching by inquiry, we also chose classroom contexts that best support full engagement by students in scientific inquiry. We investigated and described classrooms to identify those that provided “relevant opportunities for action” (Young et al. 1997, p. 140). The inquiry context requires teachers to be facilitators rather than information deliverers, as the outcomes are unknown and there was no single “right” approach to experimental design or data analysis during the inquiry.

Methods

A case study approach was used to study in-depth the inquiry teaching practice in two classrooms to best categorize the complexity of students' reasoning (Merriam 1998). Purposeful and convenience sampling was used to identify research sites (Patton 1990) to ensure that the inquiry could be observed in its entirety. Data sources included teacher and student interviews, classroom observations, and artifacts, such as student work, teacher handouts, supplemental materials, and online school information (Denzin and Lincoln 1994; Merriam 1998; Stake 1995). The data were analyzed by categorical aggregation to identify classrooms that represented “best case scenarios” for inquiry teaching, analyze the curricular context for its potential to engage students in complex reasoning, and categorize the complexity of students' reasoning.

Participants

Participants for this study, Bonnie and Janet and their students, were identified through purposeful and convenience sampling (Patton 1990). Through extensive literature review, we identified key features of classrooms that are “best case scenarios” for teaching by inquiry: teacher readiness to teach by inquiry, teacher enthusiasm for inquiry, informed teacher conceptions of inquiry, teacher confidence regarding student learning, student readiness to participate in inquiry, and support for inquiry outside the classroom (Crawford 1999, 2007; Hofstein and Lunetta 2004; Loughran 1994; Marx et al. 1994; NRC 2000; Roehrig and Luft 2004; Wallace and Kang 2004). The interviews, class observations, and documents were reviewed for evidence of these features.

Bonnie is a female European American with 10 years experience teaching high school science, including biology and chemistry as well as an introductory research course, which is a requirement for all students enrolled at her school. Bonnie completed a bachelor's degree in biology and a master's degree in liberal studies, conducted research as an undergraduate, and initially pursued a graduate degree in science before becoming a teacher. Her school is a specialty public school with a curricular focus on math, science, and technology. Students are chosen for school admissions via an application process in their home school systems, which include both rural and city districts. One of Bonnie's first year biology classes participated in the study. This class was a dual-enrollment course (i.e., students could earn high school and college credit) with sixteen eleventh graders enrolled (nine females, seven males, two ethnic minorities). Bonnie had implemented *PREP* with other classes prior to this study.

Janet is a female European American with 10 years experience teaching science, including middle school earth science and high school biology. Janet earned bachelor and master's degrees in education and a master's degree in environmental science. She conducted research as an undergraduate student and has experience working with projects for the US Army Corps of Engineers and the US Geological Survey. Janet teaches at a private school that values its emphasis on curiosity and inquiry and its preparation of students to matriculate into competitive colleges. Janet's students, twenty eleventh and twelfth graders (16 female, four males, three ethnic minorities), were enrolled in biology and had participated in other inquiry-based activities with Janet during the school year before starting the *PREP* inquiry. Janet learned about *PREP* during a conference and was excited about including it in her curriculum for the first time.

Best Case Scenario Criteria

Janet's and Bonnie's classrooms provided extraordinary environments for students to participate in inquiry. Bonnie and Janet were enthusiastic about their students' involvement in inquiry. Bonnie talked about the rarity of involving students in original research, particularly with connections to required course content and meaning within and beyond the classroom:

> I think it's so great for the kids to have something where they don't know what's going to happen and nobody knows what's going to happen. And, also feeling like they're contributing a part of scientific research and the connection with the scientist that [the students] make, I think, is really unique (Bonnie, interview).

Janet's own experiences conducting science research enhanced her interest in providing similar opportunities for her students:

> I have experienced firsthand how exciting it is to do independent work, independent research, and so I want to give them that opportunity and not just make them memorize things (Janet, interview).

Both teachers described conceptions of scientific inquiry that are compatible with currently accepted definitions (NRC 2000). Bonnie emphasized involving students in asking questions with unknown outcomes and described several essential features of scientific inquiry. Both teachers attested to the alignment of the inquiry context with course content that students were required to learn. Janet appreciated the connections between the experiments and course content and how her students' learning about plants might be enhanced. Neither teacher was concerned that the inquiry would interfere with students' learning other content in a timely fashion. The private school context of Janet's class provides “flexibility” in curriculum design. Her students do not take the end-of-course test mandated by the state, alleviating the test-preparation pressure commonly noted by public school teachers. Bonnie was confident that her students would pass the end-of-course test because they passed a similar test earlier in the year.

Neither teacher had classroom management problems, and their students rarely required outside motivation as they progressed through their inquiries. Both teachers took on the roles of guide and advisor, often answering students' questions and acting as sounding boards for students' ideas. Students in both classes had previous experience with scientific inquiry and their schools were supportive of student engagement in inquiry. Students at Bonnie's school were expected to conduct several independent science experiments during their high school careers and were supported in participating in local, regional, and national science fairs. While Janet's school did not have the same emphasis on scientific inquiry, the school advertised an environment of inquiry. Other teachers in her science department aimed to engage students in independent research (Janet, interview). Also available to both teachers was support from scientists at a nearby university who were interested and willing to collaborate with them.

Data Collection

Semi-Structured Interviews with Teachers and Students—Prior to starting the inquiry, both teachers were interviewed using a semistructured approach (Merriam 1998) to gain insight into their fit with the best case scenario criteria outlined above. Teachers were asked to explain their interest in teaching with this inquiry (i.e., *PREP*), what they knew about it, how they saw it fitting into their curricula, and how they were planning to teach the inquiry. Teachers also identified their objectives for the students' participation in the inquiry and explained their perception of what it means to do scientific inquiry.

The teachers were interviewed as often as possible on the days that the students conducted inquiry-related activities. Teachers were asked to reflect about the day's activities, how students had made decisions related to their inquiry, what they were planning for the next time the students worked on their experiments, what had been going on in class since the last researcher observations, and if there was anything that they would change about the inquiry. Teachers were interviewed a final time after students had completed their inquiry-related work. Teachers were asked to reflect on the entire inquiry experience, how they might change their teaching of the inquiry if they taught it again, what they thought worked well, and what they might change about the whole experience.

Eleven students were interviewed in groups using a semistructured format at the end of the inquiry. Students were asked to talk about the purpose of their experiments, identify their dependent and independent variables, discuss what decisions they had made during the inquiry and their rationale for these choices, describe what they learned from conducting the experiments, and share how their ideas about doing science had changed.

Classroom Observations—The classrooms were observed to learn about the inquiry settings, the general practice of inquiry, and student engagement in the methodological and cognitive processes of inquiry. The second author, as a participant-observer (Gold 1958; Merriam 1998), became familiar with both class environments and observed activities related and unrelated to the inquiry. Of special interest were students' actions, teachers' efforts to support inquiry practice, and interactions among students, teachers, scientists, and *PREP* staff. The teachers' informal management style allowed for easy movement around the classrooms to get a closer view of students at their work and interact casually with them, including posing questions (e.g., What treatment are you thinking about exposing your plant to? How did you decide to use a pH 5 solution? How did you decide to observe plant height?). Field notes were written during observations. The teachers dedicated different amounts of time to the inquiries (8 weeks for Bonnie's students, 6 weeks for Janet's), but both teachers intertwined the students' experimental work with other biology lessons. As it was not possible to observe every classroom every day, the days that students made major decisions about their inquiries (such as deciding on variables and treatments) were given highest priority. Student work and teacher and student interviews provided insight into activities on days when observations were not made.

Related Documents—Teachers shared their handouts, quizzes, tests, and exams that related to the inquiry, including copies of final laboratory reports and other student work (e.g., literature reviews). Additional information was gathered from school administrators (e.g., student and teacher demographics, course descriptions), school web sites (e.g., school mission and philosophy statements, science program descriptions), the *PREP* web site (e.g., PREP *Classroom Guide: Frequently Asked Questions*), and the state Department of Education (*Science Standards of Learning Curriculum Framework—Biology*).

Construction of a Complexity of Scientific Reasoning During Inquiry (CSRI) Matrix—To categorize the complexity of students' scientific reasoning during inquiry, we constructed a matrix (i.e., Complexity of Scientific Reasoning during Inquiry (CSRI) matrix; Table 1) through an iterative process involving the authors (Dolan: scientist and science educator; Grady: science educator) and an additional scientist. Although the work of Chinn and Malhotra (2002) served as inspiration, their matrix was altered significantly to generate the CSRI matrix and address the goals of this study. In order to create a matrix that captured the range of high school students' reasoning during scientific inquiry, we repeatedly consulted the literature about scientific inquiry, science practice, and cognitive development (Brainerd 1978;Duschl 2003;Hodson 1998;NRC 2000;Piaget and Inhelder 1969;Valiela 2001).

We divided the cognitive processes of reasoning into four levels of complexity along a continuum: least, somewhat, more, and most complex, with most complex reflecting the depth of reasoning associated with the work of research scientists and least complex representing the limited reasoning involved when information is provided to students rather than gathered or reasoned by them. For example, regarding experimental controls, lack of consideration of controls would be categorized as least complex while thoughtful decision-making and argumentation about variables that need to be controlled and how to control them would be categorized as most complex. To make distinctions among the four levels, especially between somewhat and more complex reasoning, we considered the extent to which students were explicitly engaged in a reasoning by the teachers' design (e.g., class discussions, assignments) and the extent to which students' connected their analytical and evaluative thinking to the inquiry. For example, students may give limited attention to controls because the class discussion or written instructions only require students to give them cursory consideration (somewhat complex). More complex reasoning about controls would result from student involvement in intentional, explicit consideration of the controls, including how particular controls are scientifically relevant to their experiments. We would like to emphasize that, although the matrix is organized from least to most complex reasoning, we are not implying that there is always more value in high school science that engages students in reasoning at the most complex level. The NRC (2000) reminds science educators that factors such as student readiness to conduct inquiry and teachers' goals for the inquiry will shape the implementation of classroom inquiry and thus influence the students' levels of reasoning.

Categorization of Reasoning

We first used the CSRI matrix to categorize the opportunities presented by the inquiry context for complex student reasoning. Then, classroom observations, student interviews, and student work were reviewed to identify evidence regarding the complexity of their cognitive processes during their inquiries, which then was mapped onto the CSRI matrix to show the bigger picture of the complexity of students' reasoning throughout the inquiry.

Trustworthiness

The goal of this study is the description and pilot of an analytic tool that teachers can use to recognize when students are engaging in complex reasoning throughout inquiry, rather than to generalize findings across the larger population of high school classrooms. Strategies were used to maximize the trustworthiness of the findings and analysis (Lincoln and Guba 1985), including (a) making classroom observations as frequently as possible during the inquiry, (b) repeatedly interviewing teachers, (c) triangulating data sources, (d) involving other scientists and educators in the development of the CSRI matrix and both authors separately analyzing the *PREP* context for potential complexity of reasoning, and (e) including multiple sites in the final analysis.

Findings

Categorizing the Potential for Reasoning Within the Inquiry Context

Since curricular materials can limit the complexity of learners' reasoning, we used the CSRI matrix to characterize the inquiry context (Table 2). Specifically, we determined at what level of complexity students could engage in reasoning within *PREP*. Our primary data sources were the PREP Online Lab Notebook (2009) and the PREP Classroom Guide: Frequently Asked Questions (2005), which are available to participating teachers, students, and scientists.

For the most part, the inquiry context does not appear to impose limitations on students' reasoning. In the PREP Online Lab Notebook (2009), teachers are introduced to one of the purposes of *PREP*: for students to engage in authentic scientific inquiry by conducting investigations “under experimental conditions of their own design aimed at discovering the function of the gene” (p. 1). While the PREP Classroom Guide: Frequently Asked Questions (2005) does provide methodological information, these are only suggestions and students and teachers have significant freedom and responsibility for making decisions about experimental design (an example of most complex reasoning during “Designing and conducting the research;” Table 2). For example, even though five different plant structures and multiple characteristics of each structure are listed as possible variables for students to observe and record, *PREP* does not require that students choose from these lists. The Frequently Asked Questions (2005) repeatedly note that *PREP* work is student-directed. The guidelines limit the design process only to increase the likelihood that students will complete their investigations successfully (e.g., the plants complete their life cycle, the experiments are safe to conduct). Students are asked to design their experiments such that (a) they do not intentionally kill the plants, (b) their treatments are relevant to plants, and (c) the designs can be implemented in the classroom. Additional recommendations include suggestions that students consider the severity of their experimental treatments, when they should start the treatment, how long they should continue the treatment, and how often they will expose the plants to the treatment. Since *PREP* does not require particular methods of data recording, analysis, and interpretation or specific mechanisms for communicating findings, the *PREP* context does not pose any limits to students' levels of reasoning about their investigations as they work with their data and present their results (most complex).

The *PREP* context does limit the complexity of students' reasoning in generating research questions (more complex). The over-arching research question is pre-established, namely “What role does the disabled gene play in the plant's ability to cope with an environmental stress?” Within this larger question, students have the freedom to generate sub-questions, for example, students might be interested in investigating the possibility that the disabled gene may play a role in the plant's responses to drought conditions.

Categorizing Students' Reasoning During Inquiry Practice

Having determined that *PREP*, with a few pertinent exceptions, could serve as a setting for complex reasoning, we used the matrix to categorize students' reasoning (Table 2). We sought to document the most complex reasoning observable, but did not attempt to determine whether all students were engaged at a specific level of complexity or to identify the range of their reasoning. Data are offered to support our categorizations and to illustrate how the matrix could be used by educators to categorize curricula and their students' reasoning during inquiry.

Generating Questions—Students in both classes were involved in somewhat complex reasoning as they generated questions during their investigations. Yet, students did not appear to pursue these questions further or base these questions on additional research or exploration. Some questions grew out of discussions among students, Bonnie, and *PREP* scientists. For example, one team was investigating the effects of juglone, a chemical released by black walnut trees that inhibits growth of neighboring plants, to determine if the disabled gene has a role in the plant's reaction to this chemical. The scientist and students wondered if the black walnut itself is affected by juglone and how juglone might exert its effect (Bonnie, observation). While the inquiry context allowed for more complex reasoning, Janet's students based their questions on their own observations while Bonnie's students based their decisions on prior knowledge and discussions with a scientist (somewhat complex reasoning).

Posing Preliminary Hypotheses—Because the *PREP* context does not demand or preclude the posing of preliminary hypotheses, teachers can engage students in formulating testable, relevant, and falsifiable preliminary hypotheses based on their learning objectives. Students in this study did not pose hypotheses prior to designing their experiments. Omitting this aspect of preparing to conduct their experiments came from a recommendation of *PREP* staff when he visited the classes to help the students get started on their experiments. He explained to Janet's class, that the students' experiments are “hypothesis-generating” rather than hypothesis-testing experiments (Janet, observation), meaning that hypotheses may be developed about the plants' differing responses to treatments based on students' findings. This aspect of formulating hypotheses will be discussed when we examine the students' cognitive processes related to explaining results.

Designing and Conducting the Research Study

Selecting Variables: Students in both classes were given flexibility in choosing their dependent and independent variables. Janet's students based most of their decisions on personal knowledge and interest (somewhat complex reasoning). For example, when asked how she decided to treat the plants with a copper (II) sulfate, one student explained that she “recognized it ‘cause I used it last year in chemistry…we’re trying to see what…pollutants do to plants and how bad is it, whether the gene perhaps affects it in some way” (Janet, student interview).

Janet's students also engaged in somewhat complex reasoning when they chose which features of the plants to observe (dependent variable) from interest and prior knowledge. One group who created drought conditions for their plants collected data about stem strength because they knew that plant wilting was caused by lack of water (Janet, student interview). Although students provided reasons for selecting variables based on their own experiences (vs. having variables provided), there was little evidence that students in Janet's class gave more than passing thought to the rationales for their choices.

When choosing treatments, Bonnie's students generated their own ideas and then supported their ideas with more information obtained through web searches. The students cited sites that were scientifically credible, including scientific journals that were available online as well as sites supported by the National Science Foundation and university science and agriculture extension groups. The complexity of one student's reasoning was evident when she talked about the process of choosing a treatment:

> Well, when we were learning about flavonoids, it talked about how a lot of times that could be used in pigment and then I remembered that a lot of times acidity of soil can affect pigment of flowers…We had to research acidity because we really didn't want to kill the plants. We didn't know how to [set up the experiment]. We decided to make the soil more basic and had to figure out what kind of [pH] range to use. We did a lot of looking at [information about] hydrangeas (Bonnie, student interview).

Bonnie's students collected data about many features of the plants as they matured. Their reasoning for this was categorized as most complex, in that they were unsure which features of the plant would be affected by its genotype and their treatments. Thus, they allowed their dependent variables to evolve as their experiments progressed. A student explained her reasoning: “You measure more than one thing… you weren't really sure what you were looking for when you started so you measured more than one” (Bonnie, student interview).

Considering Control Conditions: Students in both classes gave little to no explicit attention to the idea of controlled conditions (e.g., humidity, temperature). Janet did not ask her students to discuss these controls in their final lab reports, but the subject came up briefly during two class discussions (somewhat complex). Early in the inquiry, Janet led a whole-class discussion about writing about experimental methods. During this discussion she posed the question, “What are some of the controls you have?” (Janet, observation). After several students made suggestions, Janet reinforced their ideas and added her own to the list: “planting procedure, amount and type of soil, amount of light, height of light above the soil.” Similarly, there was no evidence that Bonnie's students considered controls when designing their experiments (least complex reasoning). Bonnie did not require her students to explain controls in their final lab reports and students offered no such explanations.

Explaining Results

Considering the Meaning of the Representations of Data: Students in both classes recorded their observations, re-presented their data in various formats, and ascertained meaning in their findings (most complex reasoning). Notably, less in-class time was dedicated to these tasks, and more responsibility was placed on students to accomplish these tasks outside of class. Although Janet's students were provided with data sheets for recording their observations, some students collected data in other ways, including taking digital pictures to document changes in the plant features of interest to them (Janet, observations, lab reports). After her students had finished collecting data, Janet led a whole-class discussion about how to choose the style of graph (e.g., bar graph, line graph) to represent the changes in the plants (Janet, observation). Students represented the changes in their plants with photographs and graphs they created using Excel, using both to make meaningful comparisons of their plants on particular days and across time (most complex; Janet, lab reports, student interviews). Students who collected data about leaf colors created a color scale that they used to make comparisons among their plants (Janet, lab report). A team that treated their plants with saltwater summarized their findings based on patterns in their graphs and plant colors:

> The control plants with the disabled gene grew the fastest, but over time the experimental plant with disabled genes was taller. Over all, both plants with disabled genes grew taller than both wild type plants. In terms of color, both experimental plants were lighter than both of the control plants, but the wild type was greener than the plant with the disabled gene (Janet, lab report).

Bonnie's students documented numerical and descriptive data in lab notebooks each day they worked with their plants. They re-presented their data using photographs and graphs they generated using Excel, analyzing their data on particular days and across time. They used simple statistics to gain insights into the meaning of their findings. For example, they compared means and conducted *t*-tests using MiniTab to determine statistical significance of their results (most complex; Bonnie, lab reports, student interview). One team grew their experimental plants in basic soil and found a statistically significant difference in the number of flowers across treatments (Bonnie, lab report).

Considering Limitations or Flaws of Their Experiments: Although students in both classes gave some consideration to the limitations or flaws of their experiments, students in neither class adjusted their experiments because of these limitations. Janet did not ask her students to report on limitations or flaws in their final lab reports. Yet, after their experiments, she asked them to consider sources of experimental error, which they reported on in their lab reports:

> It was some difficulties with the watering process that could have affected our results. Two times during the experiment the experimental plants received the same amount of water as the control plants out of reasons beyond our control (Janet, lab report).

Brief consideration of experiment limitations and flaws also occurred during the class discussion in which Janet drew out her students' ideas about what had gone wrong. Students reported errors that were simple and methodological in nature and did not effect change during the students' inquiries (somewhat complex reasoning), such as, “It would have better if we'd had longer,” “I had trouble counting bolts and the flowers,” and “Maybe have more than four pots of plants—we dropped one pot” (Janet, observations).

Bonnie did not dedicate class time to this type of discussion, but her students were expected to discuss significant limitations of their experiments in their final lab reports. Her students reported more sophisticated sources of error (more complex reasoning); for example

> There were many limitations to this experiment. The time allotted for measurements was only enough to collect a small amount of data…Only the phenotypes were observed such as height, diameter, and surface area. The length of the lab was limited as well…other errors could have occurred when the plants lost light or dark time when they were taken out to be measured which usually took an hour… The program, ImageJ, was used for the first time in this experiment. There were many factors that could have affected the surface area [of the plants]. If the plant is tilted one day [when the photo is taken] and not the next day then the surface area will [appear] smaller suggesting that the plant got smaller. Also an error occurred when calibrating the images (Bonnie, lab report).

Connecting Data to the Research Question: The larger scientific goal of the inquiry is to yield insights into the function of the plants' genes. While some students did not comment on the gene function in their final lab reports, a number of students in both classes made statements about the role of the disabled gene in the plant's ability to cope with the stress of the treatment (more complex). By contrasting data from the four different groups of plants, students generated inductive conclusions about the genes they studied:

> Due to coloration differences, we concluded that the missing gene had a direct effect on the plants' leaf, stem, and bolt coloration. Thus, the plants with the disabled gene were left bright green, while the wild type plants were the dark purple color. Also, because of the insects' preference to the plants with the disabled gene, it is possible to conclude that the missing gene had an affect on the plants' ability to deter parasitic organisms (Janet, lab report).

The multi-layered connections made by one of Bonnie's students demonstrate the sophistication of her reasoning while considering the implications of her observations:

> The experimental groups were stressed with a change in the soil's pH, the mutant experimental plant responded to the stress. The stress on the plant may have resulted in the plant growing more quickly than the others because when plants are stressed they tend to reproduce more quickly before the end of their life cycle. This can be seen through the results in the flowering of the mutant experimental, which produced flowers before the other plants. It is inferred that the [disabled] gene caused a different response to the change in the soil's pH (Bonnie, lab report).

Bonnie's students went a step further than Janet's by pooling their data across teams, comparing their findings regarding rates of germination and bolt (i.e., stem) growth, as well as the presence of branching bolts (most complex).

Providing Suggestions for Future Research: Students in both classes made germane suggestions for improvements or extensions of their experiments. Although Janet did not require her students to address future investigations in their lab reports, she did ask her students to think about this after they had completed their experiments. The students presented several pertinent suggestions (more complex):

> In future experiments, it may be helpful for researchers to have a larger experimental group which to vary the intensity of the drought… Also, it would improve results of future experiments to have less interference – such as providing a completely controlled environment without interference of insects for the plants to grow in and a more consistent watering schedule (Janet, lab report).

Janet also led a short class discussion about recommendations for future experiments. She posed the question, “If you carry on your research, what would you do?” Students responded quickly with simple and directly relevant suggestions (more complex), such as, “Put the [grow] light closer,” and “Use different concentrations of salt and plant more seeds,” but they did not incorporate justifications in their suggestions (Janet, observation).

Bonnie's students did not discuss their suggestions for future research as a class, but they were required to discuss “ideas for future studies” in their lab reports. Some of their suggestions were inspired by discussions with their partner scientist and demonstrated deeper consideration of their treatments. Some implied revised hypotheses (most complex), for example.

> To expand on this experiment, the acidity level in the aluminum solution could be lowered to determine whether lowering the acidity level in the solution affects the amount of aluminum that [binds to the soil and how much] reaches the plants and how it affects the growth of the plants (Bonnie, lab report).

Communicating and Defending Findings: Students in both classes communicated and defended their findings in writing in a format similar to conventional scientific reports. Bonnie instructed her students to include the following sections: introduction, results, statistical analysis, and conclusion (Bonnie handout). They also turned in lab notebooks in which they had recorded their procedures and observations. Janet's instructions for a more abbreviated paper asked students to include their research question, procedure, results, conclusion, appendix (including images, tables, graphs) and bibliography (Janet, handout). A number of students in both classes used their findings to support their conclusions (most complex). For example, a student in Bonnie's class compared his data with the entire class's data, referred to his use of statistical analyses, and offered two hypotheses that could explain his findings:

> The most obvious conclusion from this experiment is that the amount of light affects a plant's size and overall health…Following statistical analysis, there was a significant difference between the effects of the different light groups…From the class data, significantly more wild-type plants germinated before the mutant plants. However, the mutant plants seemed to bolt first overall. Perhaps the mutant's gene helps the plant to mature faster after germination; this would account for the greater number of bolts on the class's mutant plants. [Our scientist partner] said that flavonoids are involved in the production of sunscreen. Since the wild-type plants for the control and Exp. 1 appeared to be healthier on May 10, maybe they contain a flavonoid that helps to protect them from too much light (Bonnie, lab report).

Discussion and Conclusions

Modeling of inquiry teaching in science teaching methods courses is not sufficient to prompt future teachers to teach by inquiry (Bryan and Abell 1999; Crawford 2007; Keys and Bryan 2001). Critical examination of the value of inquiry teaching in real classrooms is a necessary experience for teachers to change their beliefs in a way that changes their practice. We set out to develop a tool for scaffolding this change by bringing to the fore instances when teaching by inquiry engages students in complex scientific reasoning. Our analysis of the inquiry context demonstrated that *PREP* provided opportunities for engagement in complex scientific reasoning. Because the over-arching research question is provided by *PREP*, students only have freedom to ask sub-questions. This structure limits student-directedness during inquiry teaching, but is an authentic reflection the apprenticeship of future scientists, including undergraduate, graduate, and postdoctoral students. Such training is typically supported through extramural funding acquired to address a larger question connected to a senior scientist's ongoing research and framed by the body of knowledge and the availability of equipment and materials. Student-directedness and scientific meaning are two sides of the inquiry teaching coin that teachers must learn to balance, the first being critical to student motivation and ultimately learning (Roth et al. 2008) and the second providing a glimpse into the unique social and intellectual dynamic of science practice. The latter also serves as a motivator for students by making concrete the value of their work as a contribution to the scientific community (Dolan et al. 2007). We propose that teachers use the matrix to maintain a balance between authentic learning and authentic science, rather than prioritizing one while sacrificing the other (McDonald 2004).

Rather than focusing on individuals or groups of students as our unit of analysis, we chose to take a more holistic view of inquiry teaching in these classrooms to identify points where students reasoned at the most complex levels as well as times where no students appeared to reason with complexity. This approach revealed universal gaps in students' reasoning that may have otherwise been missed. For example, controls are integrated into the *PREP* design, with wild-type plants serving as standards for comparison with mutants, and untreated plants serving as standards for comparison with treated ones. Rather than ensuring design of high-quality controls, this implicit approach may have moved consideration of controls under the teachers' “instructional radar” such that they were not integrated explicitly into inquiry teaching practice. Teachers learning to teach by inquiry could use the matrix to recognize inquiry elements that are implicit aspects of curricular design and bring these elements to the instructional forefront.

Negotiating the ambiguous and dynamic nature of inquiry teaching remain major sources of discomfort for teachers and students alike (Crawford 2007; Hung et al. 2003; Frykholm 2004; Loughran 1994; Yerrick 2000). Even Bonnie's students, who maintained openness in their plans for data collection, eventually became caught in a lock-step approach. The students set out to use ImageJ software to compute the surface area of the plants' leaves from top–down photographs of the plants. As the plants grew, the leaves overlapped and curled in such a way as to preclude accurate documentation of leaf surface area using simple top–down photography. Students lamented this complication and reported it to Bonnie, but neither generated possible approaches to address it, seemingly unable to let go of the “scientific method” they had planned at the outset. We propose that teachers use the matrix to scaffold decision-making during inquiry teaching in a way that leads out of the lock-step of the “scientific method” and legitimates the ambiguity and dynamicity of authentic inquiry.

Our results also revealed that students were attributing unanticipated results to human error. Students in Janet's class restrained their discussion of experimental limitations or flaws to methodological errors, for example, that one pot of plants was dropped or that the plants could have been watered differently. The assumption appeared to be that, if their results were not as predicted or did not lead to a definitive conclusion, the only causes were their own experimental missteps rather than that all experimental designs have limitations or that there may be biological meaning in unanticipated results. We propose that teachers use the matrix as a lens during inquiry teaching to recognize that the discussion about unanticipated results can move beyond simplistic methodological causes (e.g., human error) to more complex alternative explanations.

Implications

As science teacher educators, we see potential for using the matrix as a tool for systematically guiding teachers in recognizing when students' inquiry is more “doing” versus reasoning. We believe that the matrix has the potential be a powerful tool for challenging and enabling teachers to think differently about their practice by encouraging reflection and breaking “patterns of thought and action” (Putnam and Borko 2000). Categorizing students' reasoning is a first step in informing changes in inquiry teaching practice to better support students in reasoning. We propose that teachers can use the matrix described here to better appreciate when students are caught in the lock-step of a scientific method that has been prescribed unnecessarily. Similarly, the matrix can be used to diagnose students' needs throughout the academic year to inform instructional choices in a way that emphasizes different cognitive processes of inquiry as students' skills develop over time. Points along the continuum of reasoning complexity are ready-made for purposeful reflection by teachers as they learn to teach by inquiry in a way that balances their learning objectives and readiness to support students in complex reasoning with students' motivations, students' readiness for complex reasoning, and the availability of resources (e.g., time, equipment, materials, and space).

We propose that teachers use the matrix to evaluate curricular materials purposefully and systematically, as the authors did here with *PREP*, to decide whether certain inquiry learning experiences are appropriate given their objectives for enhancing students' reasoning skills and their students' current reasoning abilities. Davis (2006) found that, in their critique of instructional materials, preservice teachers valued inquiry curriculum because it would be motivating for students, but not because it modeled the authentic practices of science or afforded opportunities for students to reason. Use of the matrix could support preservice teachers in learning to adapt and use inquiry teaching materials effectively while making explicit the potential that teaching by inquiry has for engaging students in complex reasoning.

We also imagine the benefits of the matrix as a tool to encourage dialogic inquiry in teacher-scientist partnerships in a way that supports students in complex reasoning and teachers in planning and implementing inquiry. Many have advocated for teacher-scientist partnerships as a mechanism for benefiting everyone involved (Dolan and Tanner 2005; Elgin et al. 2005; Moreno 2005; Siegel et al. 2005; Tomanek 2005; Trautmann and MaKinster 2005). Research collaboration like PREP is one model for partnership, in which the primary objective for students is understanding of the concepts, processes, and nature of science and for scientists is developing new scientific knowledge (Fougere 1998; Lawless and Rock 1998; Spencer et al. 1998; Tinker 1997). Although an early study of one such partnership did not reveal transformations in teaching practice (Means 1998), some teachers have reported shifts to teaching by inquiry that result from partnerships with scientists (Laursen et al. 2007). Teachers attributed these changes to observing how a content expert approached a lesson and having the opportunity to “step back and focus on student learning” (Laursen et al. 2007). Yet, Nelson's characterization of teacher-scientist partnerships that aimed to support “teachers in shifting to inquiry-based practice” (2005) revealed that only one of the partnerships she studied had a stance of knowledge negotiation through dialogic inquiry and coparticipation that led to changes in teaching practice. The knowledge consultation stance of the other partnerships was attributed in part to the partners' lack of experience in creating relationships based on dialogic inquiry without scaffolding. We propose that the process of applying the matrix and considering the results serve as a launch point for dialogic inquiry that takes a sustained, critical view of the practice of teaching by inquiry.

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Table 1

Matrix for evaluating complexity of reasoning during scientific inquiry

Cognitive process	**Increasing complexity of scientific reasoning tasks**			
	Least complex	**Somewhat complex**	**More complex**	**Most complex**
Generating questions				
	The over-arching research question is provided; students do not generate or explore other questions during the inquiry	The over-arching research question is provided; students generate and/or explore other questions based on observations during the inquiry	The over-arching research question is provided; students generate and/or explore other questions based on observations and wider exploration of the research topic during the inquiry	Students generate their own research question; other questions are generated and explored based on observations and wider exploration of the research topic during the inquiry
Posing preliminary hypotheses				
	Students do not pose preliminary hypotheses or they pose non-testable or irrelevant hypotheses without conducting prior investigations into the research question	Students pose relevant and testable preliminary hypotheses without conducting prior investigations of the research question	Students pose relevant and testable preliminary hypotheses based on prior investigations of the research question	Students pose relevant, testable, and falsifiable preliminary hypotheses based on prior investigations of the research question
Designing and conducting the research study				
Sub-processes				
Selecting dependent and independent variables	Students do not have a rationale for their choice of variables	Students have a limited rationale for their choice of variables	Students have a thoughtful, non-technical rationale for their choice of variables	Students have a thoughtful, scientific rationale for their choice of variables
Considering experimental controls	Students give no attention to the design of controls	Students give minimal attention to the design of controls	Students give some attention to the design of controls	Students give purposeful, focused attention to the design of controls
Explaining results				
Sub-process				
Considering the meaning of the representations of data	Students are provided with a formatted data table and do not consider meaningful representations of data	Students design their own data tables giving little consideration to the meaning of representations of data	Students represent data in multiple ways including tables, drawings, graphs, photographs, or statistical representations with little consideration of the meaning of representations	Students represent data in multiple ways including tables, drawings, graphs, photographs, or statistical representations, thoughtfully considering the meaning of representations
Considering the limitations or flaws of their experiments	Students do not consider or report limitations or flaws of their experiments	Students consider superficial limitations or flaws of their experiments at the end of the inquiry and report these limitations or flaws orally or in writing	Students thoughtfully consider limitations or flaws of their experiments during the inquiry but do not make adjustments in inquiries. Students report these limitations orally or in writing	Students thoughtfully consider limitations or flaws of their experiments during the inquiry and adjust inquiries accordingly.
Connecting data to the research question	Students do not connect data to research questions	Students use their data to answer questions other than the primary research question	Students use different forms of reasoning (e.g., contrastive, deductive, inductive) to connect	Students use results from different studies, as well as different forms of reasoning (e.g., contrastive,

Cognitive process	Increasing complexity of scientific reasoning tasks			
	Least complex	**Somewhat complex**	**More complex**	**Most complex**
			data to the primary research question. Reasoning may require inferences involving several layers of connections	deductive, inductive) to connect their data to the primary research question. The reasoning may require inferences involving several layers of connections
Providing suggestions for future research	Students do not pose suggestions for future research and do not suggest additional hypotheses	Students pose superficial suggestions for future experiments or suggest unrelated hypotheses	Students pose relevant suggestions for future experiments or suggest additional, pertinent testable hypotheses	Students pose relevant suggestions for future experiments, including pertinent testable hypotheses
Communicating and defending findings	Students do not communicate or defend their findings either orally or in writing	Students give limited attention to communicating and defending their findings orally or in writing	Students communicate their findings orally or in writing with some emphasis on defending their findings	Students communicate their findings orally or in writing. Students use logical arguments to defend their findings

Table 2
Opportunities for scientific reasoning in inquiry context and practice

Cognitive processes	**Increasing complexity of reasoning**			
	Least	**Somewhat**	**More**	**Most**
Generating questions		B, J	P	
Posing preliminary hypotheses	B, J			P
Designing and conducting the research				
Selecting variables		J		B, P
Considering experimentally controlled conditions	B	J		P
Explaining results				
Considering meaning of data representations				B, J, P
Considering limitations or flaws of experiment		J	B	P
Connecting data to research question			J	B, P
Providing suggestions for future research			J	B, P
Communicating and defending findings				B, J, P

B Bonnie's class; *J* Janet's class; *P PREP* context