The Scientific Method and Scientific Inquiry: Tensions in Teaching and Learning

Abstract
typically, the scientific method in science classrooms takes the form of discrete, ordered steps meant to guide students’ inquiry. In this paper, using the lens of activity theory, we examine how focusing on the scientific method as discrete steps affects students’ inquiry and teachers’ perceptions thereof. To do so, we study a 9th grade environmental science class in which students first reviewed a typical version of the scientific method, then brainstormed about which sites on school grounds could be good earthworm habitats and how to test their ideas. Our discourse analysis explores the dynamics between the “steps” of the scientific method and students’ engagement in more authentic scientific inquiry. We argue that focusing on the scientific method as discrete steps can distract students from their ongoing, productive inquiry and can also draw teachers’ attention away from students’ productive inquiry.

Introduction
After reviewing the steps of the scientific method with her 9th grade environmental science class, Ms. Jones asked students to brainstorm possible tests they could conduct on school grounds to explore the best habitat for earthworms. In the ensuing small-group discussion, after 86 conversational turns that did not refer to vocabulary or steps from the previous scientific method review, a group of students started mentioning the term “variables”:

87. Leslie: We should just pick a random place that doesn’t even have worms. Most like the dust.
88. Kevin: --dark area (counting the areas they have on the list). Why?
89. Leslie: ‘Cause it’d just be fun to see.
90. Chris: Well, we’d need more than two areas to have it accurate…cause more times you…get…you get--

91. Leslie: Yeah. We need variables. That’s what I mean.

92. Chris: With two variables, that’s gonna be like…

93. Kevin: So…

94. Leslie: We should do like three.

95. Kevin: So we compare them or something?

96. Leslie: (nodding.)

97. Chris: What about besides where the busses—

98. Kevin: So we could like, you mean like—

99. Chris: What about the area in the middle of the bus loop? With all the grass? So that would be a good area ’cause people run over that and that would be a variable to see if, uh…worms are buried.

100. Leslie: Yeah, but then we’ll have two changing variables. We only need one.

Although it is not clear if the students have yet settled upon a consistent or correct use of the term variable, what interests us here is how this “variable” talk relates to their scientific thinking. Is it a guidepost or a distraction? Evidence here is ambiguous. Bringing up “variables” in lines 91-92 may have helped students notice the need to “compare” (line 95) different habitats and the danger of conflating causal factors by having “two changing variables” (line 100). On the other hand, focusing on “variables” risked pulling students away from critically evaluating the factors affecting the suitability of different habitats, which was the point of this investigation. In line 99, Chris suggests that testing the bus-loop area can get at whether worms are buried or live near the surface where walkers could squash them: “So that would be a good area [to test] ‘cause people run over that and that would be a variable to see if, uh…worms are buried.” Does this idea get dropped without further examination simply because the students “only need one” changing variable and the walked-upon grassy site violates that requirement?
In this paper, we explore the dynamics among how the scientific method gets presented in a typical high school lesson, how students engage in scientific inquiry, and what teachers notice in students’ inquiry. To do so, we must first specify our definitions of “scientific method” and “scientific inquiry.” When initially used by Dewey (1910a), both terms emphasized processes underlying scientific practices. Their meanings, however, have morphed and diverged over time. In the following section, we reflect on the historical construction of these ideas. Then we present our definitions and how they fit into the ongoing discussion of “scientific method” and “scientific inquiry.” These clarifications enable us to motivate and present our research questions.

**Scientific Method and Scientific Inquiry**

**The Scientific Method: A Problematic Interpretation**

The scientific method was first introduced to American science education in the late 19th century, as an emphasis on formalistic laboratory methods leading to scientific facts (Hodson, 1996; Rudolph, 2005). It evolved towards a cognitive prescription after Dewey (1910b) summarized his analysis of reflective thinking into a five-step “complete act of thoughts.” While Dewey’s articulation was responsive to context and dynamic in nature, his theory was decontextualized, reconstructed and integrated into school science as “the only safe method,” under pressure of increasing high school enrollment and criticism of an overemphasis on laboratory method (Rudolph, 2005).

The appeal of an established, decontextualized, well articulated scientific method was obvious. It made “doing science” an easy reform to carry out; instructions for students needed minimal changes to incorporate the prescribed set of ordered steps. Over time, it became common for science educators and curriculum developers to break down
the process of science into steps (or stages) and design inquiry models centering on them (Rudolph, 2005). Many such models emerged, such as Strong Inference (Platt, 1964), Experiential Learning Cycle (Kolb & Fry, 1975), and SM-14 (Edmund, 1994, 2000).

Though differing in details, these models shared the assumption that scientific processes could be stripped from the content being investigated and summarized into a regular account. Critics of such extraction of the science method have argued that scientific investigation can take various routes (Conant, 1951) and that decontextualized accounts overlook the guiding role and interpretive nature of scientific theory (Lederman, 1998; Hodson, 1996). Arguing in particular against representing scientific processes as discrete steps, Windschitl (2004) emphasizes that such accounts fail to address how multiple steps are “often considered in relation to one another at the outset of the investigation (p.483).” Criticism of school science that distorts the nature of scientific activity reflects studies of practicing scientists that, among other aspects of practice, highlight the dynamic and social nature of how science activity typically unfolds (Collins, 1992; Pickering, 1995).

In response, some proponents of scientific method have emphasized that the steps are not rigid and do not follow a fixed order (e.g., Reiff, Harwood, & Phillipson, 2002). Even these more nuanced step-based accounts of scientific processes, when formalized for school curricula, risk getting filtered and distorted into rigid steps, as illustrated by what happened to Dewey’s contextualized and flexible “acts of thought.” Although such accounts of the scientific method are still subject to criticism, our paper does not enter into this philosophical debate.¹ We focus instead on how the scientific method is

¹ Very briefly, the deeper problem with even the more nuanced step-based accounts of scientific method is that, stripped from the local context and content of a particular scientific investigation, such descriptions
represented in high school classrooms, the effects of these rigid step-based accounts on students’ inquiry, and teachers’ perceptions thereof. In our study, the scientific method denotes step-based, decontextualized accounts of scientific process as formalized in secondary school curricula, instruction, and assessment (Rudolph, 2005).

Scientific Inquiry: What Counts as Authentic?

Scientific inquiry is another contested term. Accompanying the increased calls for inquiry teaching and learning, and the flood of “inquiry-based” curricula, ideas have emerged about what constitutes inquiry. Some associate inquiry with "hands-on" learning or activity-based instruction (Tamir, 1998; Willden, 2002); others treat it as process skills linked with the scientific method (Suits, 2004; Knabb, 2006; Ayers & Ayers, 2007). Many science educators argue, by contrast, that inquiry should focus on the thinking practices through which students (and scientists!) understand and construct scientific ideas, practices that cannot be formalized into a rigid “method.” Such practices include mechanistic reasoning, model-based reasoning, scientific argumentation, and sense-making (Lehrer & Schauble, 2004; Warren, Ballenger, Ogonowski, & Roseberry, 2001; Hammer, Russ, Mikeska, & Scherr, 2005).

Recognizing that science in a school context cannot fully duplicate what practicing scientists do, a growing body of research has explored inquiry practices in which students can engage. Lehrer and Schauble (2004) suggested an emphasis on data-modeling-based statistical reasoning. Hammer et al (2005) found that even elementary students were able to generate mechanistic reasoning for prediction and explanation, cannot account for local decision making — why scientists choose and sometimes mix particular steps at particular moments. By focusing on the steps themselves rather than the motivations and cues for choosing the steps, such accounts arguably miss the essence of scientific inquiry. This paper, however, offers a different, less philosophical critique of “the scientific method.”
distinguish different ideas, appreciate consistency in reasoning, and value replication. Warren et al (2001) gave an account of how students from diverse communities made sense of science when engaging in everyday sense-making talk. Warren and Rosebery (1995) linked such sense-making activities with scientific argumentation, suggesting that argumentative interactions can contribute to a clearer sense of scientific accountability.

In this paper, “scientific inquiry” refers to “the pursuit of coherent, mechanistic accounts of natural phenomena” (Hammer, et al, 2005, p. 13), a definition that attempts to synthesize much of the literature above. Epistemic actions and interactions that help to identify scientific inquiry include mechanistic reasoning, pursuing coherence in ideas, participating in scientific argumentation, supporting claims with evidence, formulating sensible hypotheses, attending to confounding causal factors (which often takes the form of controlling for variables), and so on (Hammer, et al, 2005; Russ, Scherr, Hammer, & Mikeska, 2008). Crucially, these activities and thought processes indicate scientific inquiry only if they occur in the service of “the pursuit of coherent, mechanistic accounts of natural phenomena.”

To recognize productive inquiry practices in the science classroom, we conducted critical analysis of classroom interactions, including those carried out in everyday language (Warren, et al, 2001); by our definition, inquiry need not involve formal scientific terminology.

**Revisiting the opening scenario: scientific method or scientific inquiry?**

Having situated our definitions of “scientific method” and “scientific inquiry” in the literature, we now revisit our opening example to motivate and refine our research questions. Prior to that snippet, we observe students engaging in productive inquiry,
providing evidence and reasoning when presenting their ideas about possible testing sites. Then Leslie brings in the term *variable* from their class’ earlier scientific method review (line 91). Our research question is, does focusing on terms and ideas from the scientific method contribute to or distract from the group’s scientific inquiry?

As noted above, the evidence in lines 91-100 is ambiguous. When Leslie says “but then we’ll have two changing variables, we only need one [changing variable]” in response to Chris’ “bus loop” idea (line 99), is she suggesting the difficulty of attributing causality with two independent variables present (grass-covered and trampled) as part of her pursuit of mechanistic accounts of natural phenomena? Or is she simply reciting a rule from “the scientific method” that is disconnected from the students’ sense-making?

In this paper, we explore the relationship between the scientific method and scientific inquiry in teaching and learning by analyzing a 90-minute high school environmental science class taught by Ms. Jones. Relying in part on the continuation of the student conversation introduced above, we documented how, without being guided by a formulaic scientific method, students could engage in productive scientific inquiry, and teachers could value that activity as productive scientific inquiry. With this established with our data, and supported by the research literature (Sherin, diSessa, & Hammer, 1993; Hammer, 1995; Warren & Rosebery, 1995; Cavicchi, 1997; Smith, Maclin, Houghton, &Hennessey, 2000; Hammer, et al, 2005; Rosenberg, Hammer, & Phelan, 2006), we then use data to argue that attending to the scientific method as commonly taught in schools(Carey & Smith, 1989; Windschitl, 2004) can distract both teachers and students from attending to students’ productive scientific inquiry.
We should also clarify what we are not arguing for. The supportive evidence to our main argument is existence proof of a phenomenon that can emerge from dynamics between activities of the scientific method and scientific inquiry. We do not make prediction on how often and under what circumstances a focus on the scientific method would interfere with productive scientific inquiry, but simply point out a phenomenon that warrants further study. In addition, this paper offers no arguments about the (in) adequacy of published models of scientific method/inquiry or about the importance of teaching identifiable steps of scientific processes to students.

**Theoretical Framework**

We have discussed above our stance towards what constitutes productive scientific inquiry in classrooms, as well as the form that scientific method often takes. To better understand the dynamics of scientific method and inquiry in a classroom, we turn to classroom discourse to closely examine the ways in which it reflects and shapes activity. We consider learning to occur continuously in interactions between the social and individual planes, mediated by material and symbolic tools (Vygotsky, 1978). We draw on activity theory (Engstrom, 1987) to establish classroom activities as connected, purpose-driven interactive processes, which calls for close examination of relationships among classroom participants’ in-the-moment attention and actions, and how that gets contextualized by previous experience and systemic environments. Similar analytical focus on activity has been presented by Valli and Chambliss (2007) in a study of two class periods taught by the same teacher.

**Methodology**
Background and Data collection

We drew on data from a three-year research and professional development project focusing on how high school science teachers attend to student thinking in the classroom. As part of this work, we regularly videotaped teachers’ classrooms and conducted accompanying interviews before and after the class, as well as when follow-up questions emerged during analysis. Data also came from biweekly teacher meetings, where teachers met with their subject-matter peers (biology, physics and environmental science) to discuss snippets of video from their own classes. For two summers, teachers also attended a week-long workshop aiming at fostering greater attention to the substance of student thinking and greater sophistication about the nature of scientific inquiry.

Participant and case selection

At the time we videotaped the class discussed in this paper, Ms. Jones was in her 5th year teaching 9th grade science at a public high school straddling suburban and urban communities just outside a city in the mid-Atlantic region of the United States. Students in her class reflect the economic and ethnic diversity of the school: More than 60% were identified as minority (primarily African American and Hispanic), and more than 20% qualified for free and reduced lunch programs. Our classroom data comes from her 9th grade environmental science class, during what she described as an “inquiry” unit on earthworms that took place in September, at the beginning of the 2006 school year. This single classroom period consisted of two distinct but related activities: (i) a review of the scientific method and (ii) brainstorming in small groups and as a whole class, to develop

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2 This work was supported by the National Science Foundation, under Grant ESI 0455711. In total we worked with 25 teachers, divided among discipline-based cohorts (biology, physics and environmental science). Participating teachers worked under the guidance of the same set of state level standards but came from various schools/school districts. There is large variance in their ages and years of practice experience.
hypotheses about where on school grounds would be the best earthworm habitats and to design corresponding field tests.

We selected this class partly because the review of scientific method typifies how the twenty-five teachers in our project — and teachers at various grade levels we’ve observed in other projects — teach the scientific method as a series of discrete steps. Our observations are consistent with those of other researchers (Carey & Smith, 1989; Windschitl, 2004). Similarly, the students’ brainstorming typifies how they are able to engage in scientific inquiry without following prescribed steps of a scientific method (Kuhn, 1993; Hammer, 2005). We also chose this episode, however, for an unusual feature: The two activities occur in the same class period. Specifically, students engage in small-group free-form inquiry immediately after participating in a review of the formulaic scientific method. This juxtaposition enabled us to compare the classroom interactions across the two activities, and to observe what happens when “scientific method” considerations enter students’ productive inquiry discussions.

This later point is significant. We have many examples in our corpus of project data in which the scientific method dominates the teachers and students’ attention, with minimal evidence of authentic scientific inquiry. For example, in a 9th grade physics classroom “investigating” Newton’s Second Law using toy cars and rubber bands, the teacher did not encourage students to talk about mechanism, and few students offered such talk, largely because the teacher wanted discussion to focus on whether students’ results proved or disproved their hypotheses. (Discussion did not turn to the implications of those hypothesis tests, which were treated as isolated facts, even when they contradicted one another.) In another high school biology classroom, following a review
of the scientific method steps, a teacher asked her class to come up with hypotheses about what would happen when you add yeast to sugar water and plain water respectively. The focus was on whether the hypotheses were phased as an “if…then…” statement (a requirement from the county curriculum guide’s version of the scientific method), with no need for students to justify their ideas before carrying out the experiments. By contrast, in Ms. Jones’ class, after the scientific method review, the teacher encouraged students to engage in extended scientific inquiry, and students did so.

The group of three students we videotaped during the small-group discussions was chosen because we could tape them easily without disrupting the class and because they consented.

**Data analysis**

We consider learning as a socio-cultural process in which participating individuals locally construct meanings through interactions (Erickson, 2004; Vygotsky, 1978), and as a goal-oriented activity (Engstrom, 1987). In this study, video-taped classroom discourse was the primary data source for interpreting how teaching and learning of scientific method and inquiry unfolded moment-to-moment. We also draw on discourse to make inferences about the explicit and implicit goals that shaped and were shaped by teachers and students actions.

Examining the classroom conversations according to our working definition of scientific inquiry (see the scientific inquiry section in the introduction), we first identified discourse instances that revealed students’ inquiry practices and ones from which we could infer little productive inquiry thinking and reasoning. We then analyzed both types of instances employing discourse analysis (Gee, 2000; Kelly, 2005), interpreting the
underlying meanings of specific learning interactions by taking into account immediate conversational contexts (e.g., considering the discourse that preceded and followed a specific line to help inform the most plausible and relevant interpretation of a student idea expressed in a conversational turn) and broader systemic contexts (e.g., considering the teaching and learning of the scientific method not as a stand alone event but as a more ubiquitous practice across school grade and supported by external assessment).

Through this selection process we established evidence for our claims about the students’ abilities to engage in meaningful scientific inquiry. Through identifying instances that were ripe for inquiry where we did not see students engage in such activity, and by focusing on episodes where shifts in the nature of activity were apparent, a close focus on discourse allowed us to draw contrasts that highlighted changes in discourse properties, such as structural patterns and use of language. This variation enabled us to distinguish different activities within the class period, and afforded the opportunity to reflect on how the goals of different activities relate to and influence one another.

After video and transcript analysis, we conducted a semi-structured interview with Ms. Jones to provide additional insights and to challenge our initial interpretations. Her reflections allowed us to better understand her perspective on what and how this community learned during this particular class. Also, the ways she justified her own actions helped reveal broader systemic influences. We crosschecked and synthesized her interpretations with our own and shared the revised paper with Ms. Jones, enabling her to correct outright mistakes and to further inform our perspective on classroom events.

Besides classroom data, a videotaped meeting of our environmental science teachers discussing video snippets from Ms. Jones’ class also allowed some insight into
how the scientific method focus impacts the way teachers attend to student ideas. The analysis of this teacher discourse was informed by Herbst & Chazan’s (2003) argument that teachers’ reactions during such meetings stem not only from their personal beliefs but also from their perceptions of what fit into group norms.

Results and discussion

Review of the scientific method: A focus on ordered vocabulary list

This 90-minute class began with a 30-minute review of the scientific method, which, as Ms. Jones told her students, was “the thing that will be on HSA” so “it’s not bad to hear it twice.” The HSA, or High School Assessment, serves as the State measurement of school and individual student achievement used to meet No Child Left Behind mandates. While the state HSA focuses on biology, Ms. Jones’ school district intends environmental science to prepare students for biology. Therefore, it came as no surprise that Ms. Jones chose this activity and format; student responses also suggested that going over the scientific method was a familiar, expected routine associated with school science.

We can summarize Ms. Jones’s actions in this 30-minute segment as follows:

a) The teacher drew students’ attention to an account of ordered steps. Ms. Jones framed her questions by using expressions such as “what is the first step” and “what comes next.” She also corrected students when they answered with “wrong” steps. For example, when a student suggested “research” as the step following “hypothesis,” Ms. Jones pointed out that “we've already done the research. We put that in with the hypothesis.”
b) The teacher drew students’ attention to the key vocabulary. Ms. Jones provided affirmation or repeated what students said when students used correct terminology for the steps and gave correct related details. On the contrary, when students did not come up with the right term, she provided further hints. For instance, she asked “We test and what do we call that?” to indicate that she was seeking a term synonymous with “test.”

c) The teacher emphasized that the steps do not overlap. When Ms. Jones asked what should be done during an experiment and a student responded with, “We're going to take notes and analyze them,” she pointed out “that's two things you just put together,” reframed her question to “What are we going to do actually while we're doing the experiment?” and confirmed “record the data” to be the right answer. Then she went back to check with the student what the “next step” was, making sure that the whole class understood analysis as a “separate step” next to experiment.

From these aspects of Ms. Jones’ actions, we infer the goal of this activity to be reviewing and reinforcing the scientific method, which was conceptualized as an ordered list of disjointed components. Students’ behaviors suggested that they were coordinating with the teacher toward this object. In the follow-up interview, Ms. Jones verified that this activity was “totally for the six steps of the scientific method.” She also emphatically stated that “students need to know these to answer the test questions.”

Since the goal is high-stakes test preparation rather than inquiry, it is not surprising that the students’ answers lacked mechanistic reasoning or coherence-building, and the whole activity resembled a “guess the word” game in which students threw out terms and the teacher tried to cue for the right vocabulary and order. Such a goal, as
embedded in similar activity patterns, appears throughout our project’s video library of physics, biology, and environmental science teachers.

A bid to change the object towards brainstorming ideas

This section describes Ms. Jones’ bid to shift the goal and type of activity away from reviewing vocabulary lists and towards generating ideas via scientific inquiry. At the end of the review, Ms. Jones first spent several minutes discussing where on campus they could locate earthworms, letting students coming up with a list of possible sites as a whole class, and then announced to students that they would now brainstorm hypotheses and experiments for testing the best habitats for earthworms on school grounds. During this transition, both the teacher and students initially continued to use scientific method language. As the instruction progressed, however, the teacher’s language became less formal and the object she was promoting became more ambiguous and open-ended:

1. Ms. Jones: So you, together in your groups are going to create this experiment and I'm going to help you as you go along. So, the first thing we have is the problem. (Ms. Jones wrote on the front board, “problem.”) What's the next thing that you all are going to write?

2. Student: Hypothesis.

3. Ms. Jones: A hypothesis. (Ms. Jones wrote on the front board, “hypothesis”) What else do you need to have for an experiment?

4. Student: Procedures?

5. Ms. Jones: Right, you have to have the procedures. (Ms. Jones wrote on the front board, “procedures”) What you're actually going to do, ok? And if you have - if you say you want to do some kind of soil test and you're not exactly sure of the procedure, that's ok, I'll help you with that. Ok? Don't not do something because you're not sure of how to do it - does that make sense?

(Ms. Jones then got “a list of materials” from students, put it on the board and added, below that, “safety precaution.”.)

6. Ms. Jones: (after assigning students into different groups) you're going to start thinking about what you are going to do. What you want to do for your procedure. You don't necessarily have to answer these in order - you can skip around, ok? And I'm going to come around and help you and make sure everybody's
on the right track and knows what they're doing...Everybody got it, sort of? It's a little ambiguous and there's a reason for that. I want you guys to start thinking, ok?

(Students checked with Ms. Jones what groups they were in.)

13. Ms. Jones: ...this is going to be a total rough draft because you're going to have a lot of ideas thrown on these papers. All your ideas, get them down there. This is going to be mainly a brainstorming and then we're going to start getting it organized into these- what you're going to do. Everybody got it?

In lines 1-5, Ms. Jones directs the students to decompose the task of “writing an experiment” into “problem”, “hypothesis” and “procedures.” Near the end of line 5, though, she starts to change course by encouraging students to think of tests they’re “not sure how to do.” This instruction deemphasized the writing of formal, complete procedures in favor of generating ideas. Then, in line 7, she translates “procedures” into the everyday expression “what you are actually going to do.” Next she emphasizes that order doesn’t matter — “you can skip around, ok?” (Here she points to a list of four items on the board: hypothesis, procedures, list of material, and safety precautions.) The focus on generating ideas rather than following a formal recipe is further emphasized with her repeated entreaty to “start thinking,” backed up by the reassurance (line 13) that this is a “brainstorming” activity to generate a “rough draft” of “all your ideas,” to be organized later (line 13).

In the follow-up interview, Ms. Jones explained the intent of her instructions and why she told students that “it’s a little ambiguous and there’s a reason for that” (line 7):

Ms. Jones: I want them to be more brainstorming, I think I also had the problem, that (inaudible), I did the scientific method, they get caught up on they have all these steps, and really I want them to [be] brainstorming ideas.

... Ms. Jones: I’ve given them all this stuff to think about. They were trying to put it in; they were trying to make it all happen. I gave...I kind of gave them all these and I said OK, now, brainstorm. I think they really thought they had to go through all these strict, you know, scientific method when I really want them...you know, we
would get that into the scientific method, But I just want them to come up with how they were going to compare their two sites.

Although Ms. Jones taught the scientific method as strict steps, she saw this rigid conceptualization of scientific inquiry as a potential constraint that students could get “caught up on” when engaged in the more free-flowing activity of “brainstorming ideas.” To her, the object of reviewing the scientific method steps conflicted with the object of generating ideas, although both were in her lesson plan for this class. Her instructions attempted to reframe the activity away from thinking about recipe-like steps and towards brainstorming ideas. As we now argue, her bid for a change in object was successful.

**Evidence of genuine scientific inquiry in the brainstorming activity**

During the brainstorming activity, the group of students we videotaped engaged in scientific inquiry, as evidenced by their causal explanations (mechanistic reasoning), scientific argumentation, attending to data reliability, and attending to control of variables. At first, they reviewed the list of sites mentioned earlier in whole-class discussion. Then, instead of following steps, their conversation flowed organically with their thinking, jumping back and forth across tasks and generating ideas beyond the tasks.

We now illustrate students’ engagement in the aspects of inquiry listed above. Our examples are not unique; these aspects of inquiry suffuse the students’ discourse.

*Causal explanation (mechanistic reasoning)*

Scholars who study scientists (Salmon, 1984) and students (Hammer, et al., 2005; Russ, et al., 2008) agree that causal (mechanistic) reasoning is part of scientific inquiry. When giving ideas for test sites or experimental procedures, the students often offered or at least alluded to cause-and-effect reasons underlying the ideas:

Kevin: Uh, top and bottom of a hill?
Chris: Yeah, that’s good.
Kevin: ’Cause of the run off.
Chris: And it’s been good because it’s been raining for the past days.
Kevin: Past few days.

Chris first mentioned the “top and bottom of the hill” idea for test sites during the whole-class discussion, but specifying no reason. Here, as Kevin repeats it, he also gives the reason “’cause of the run off.” We interpret this as shorthand for the explanation that water flowing down the hill makes the bottom a damper habitat than the top. Chris appeared to share this interpretation when he labels this strategy as “good because it’s been raining for the past few days,” indicating increases in dampness difference between the two sites. Even if our interpretation of the students’ reasoning is not fully correct, the students’ language still shows that they are formulating reasons for their test sites: the idea is good “[Be]cause of the run off,” especially “because it’s been raining…”

Another example took place during a discussion of how to get worms up to the ground to count. Kevin came up with the idea of “using a predator:”

Kevin: How about we put a predator…yeah! Let’s put a predator! And worm will be their prey and we’ll see what does the worm do to escape from its predator?
Chris: Yeah, ants.
Kevin: Ants are not predators. When they’re dead, yeah.
Chris: I’ve seen it, ants do attack worms.

Taking into consideration that the line of discussion on how to get worms up to the ground starts before and continues after these exchanges, we interpret Kevin’s first line here as containing a meaningful solution towards that problem, rather than simply bringing up some learnt vocabulary (prey and predator) or information irrelevant to their tasks. This solution, though impractical, relies on the cause-and-effect idea that the predators will chase the earthworms up, making them “escape.” Here and elsewhere, the
students did not treat the activity of selecting test sites and experimental procedures as arbitrarily listing places and methods, but engage in reasoning mechanistically for their choices.

*Scientific argumentation*

Many researchers have emphasized the central role of substantive argumentation in scientific inquiry (Warren and Rosebery, 1995; Warren, et al, 2001; Kelly & Takao, 2002; Hammer & van Zee, 2006). In this work, scientific argumentation is characterized by use of scientific evidence and reasoning to support, evaluate and modify one’s own and others’ claims. In the example below students engaged in argumentation about many issues, including whether artificial sites should be created:

Kevin:  We’ll put one wet and then we’ll put one dry. Make one wet, make one dry. Then see how many worms come up on the wet side and the dry side. Like which one do you like better?

Chris: We’re not having little buckets…

Kevin: No we can do something. We can put some in buckets and test them. It doesn’t really matter.

Chris: That wouldn’t be in the environment though.

Kevin: We’d be outside when we’re doing it. That’s in the environment.

Chris: Yeah, but it’s in a secluded area.

Kevin: Ok, ok, ok, ok, ok.

Chris: Cutting off all the other worms around the area. They’ll feel the same because you’re only using the worms from that one little area.

Kevin: Fine. Oh, how about we do this! How about we find a dry place and a damp place.

Here, Kevin suggested creating artificial habitats in buckets, one wet and one dry. Chris challenged this idea because “that wouldn’t be in the environment” and “it was secluded.” He also elaborated on why artificially-secluded sites might yield different results from natural sites: since you’re “cutting off all the other worms around the area,” the secluded worms will “feel the same because you’re only using the worms from that
one little area.” Using such personified language, Chris identified the possibility that isolated worms could behave differently from worms in real habitats, perhaps because worms from “one little area” have something in common, affecting or affected by their interactions in a shared micro-environment. We cannot tell whether Kevin accepted or merely acquiesced to this reasoning; but based on the in-situ alternative he proposed at the end, he appears to have understood Chris’s point.

Note that a literal enactment of the teacher’s instruction to brainstorm freely — “all your ideas, get them down there” — might have led Chris to accept Kevin’s artificial-habitat idea (while perhaps proposing another possibility), or Kevin to stick with his idea (while also proposing another option). Their authentic inquiry, however, involved evaluating and debating ideas rather than just listing them.

Attention to confounding causal factors (control of variables)

The point of controlling for variables, of course, is to tease apart potentially confounding causal factors. Without employing the vocabulary or steps often associated with school-taught control of variables lessons, the students attended to the issue of confounding causal factors, as illustrated by the above argument over artificial wet and dry environments. Kevin’s two-bucket experiment showed a tacit understanding of independent variable (dampness), dependent variables (earthworm’s preference) and control (dry soil as control to wet soil). Challenging Kevin’s experimental design, Chris showed an understanding that, when exploring ecological systems, artificial environments can introduce confounding causal factors — “cutting off all the other worms around the area” — that alter the interpretation or generalizability of results.
Attention to data reliability

Without appearing to rely on school-taught rules for obtaining reliable data, the students attend to reliability:

Chris: We’ll need something to separate worms because what if there’s one area where there’s like fifty different worms that all crawl up in one area? It’s like one…oh two…oh wait…three…I think you already counted that one!

Chris realizes that, without separating already-counted worms from the rest, counting errors could occur. We also saw attention to data validity/reliability above, when Chris noted that it’s been raining the past few days, thereby ensuring that the run-off soaked habitat at the bottom of the hill differs from the drier habitat at the top. Another example occurred when Chris suggested using a sound-generating device to annoy the worms into coming to the surface (for easy counting), while Kevin suggested they just “dig and look.” Chris argued that digging might mess up their counts because (i) the earthworms might move away before you get down there, and (ii) digging might cut some earthworms into two.

In brief, this brainstorming activity showed students’ ability to do genuine inquiry, once the object switched from reviewing the steps of the “scientific method” to generating ideas. Evidence of inquiry included students’ causal explanations, argumentation, attention to data reliability, and attention to confounding causal factors. Students treated their site and test selections not as elements of a list they needed to check off, but rather, as ideas to be explained, argued about, and refined.

In the follow-up interview, Ms. Jones expressed satisfaction with this activity:

I thought it went very well. I was happy. I was, like I said, I was impressed they had such a, and this is just an example [referring to the student group we specifically taped]. The class as a whole covered so many aspects of comparing the habitats. And I think they really thought about ways to test the habitats. You know, because I told
them, don’t worry about the logistics, just tell me what you wanna test, and like if you don’t know how to do it… I thought that was fantastic.

Ms. Jones, like us, noticed students’ productiveness in generating ideas when brainstorming and partly attributed such success to her removing the restrictions set by the former review on scientific method. The next section provides evidence that the activity shift she purposefully conducted (as described in previous section) made it possible for such genuine inquiry to take place.

When goals collide: “Scientific method” talk in brainstorming activity

So far, we have argued that

(1) during the beginning review on the scientific method, the teacher and students attended to vocabulary and proper ordering as well as disentanglement of steps, which served the purpose of test preparation, and unsurprisingly, resulted in little evidence of scientific inquiry; and

(2) during the later brainstorm activity with the object of generating ideas, students engaged in productive inquiry practice without sticking to the steps and terminology of “the” scientific method.

We now build on these conclusions by examining two instances in which talk of the scientific method entered into the students’ brainstorming activity. Rather than organizing or otherwise buttressing students’ idea generation, attending to the scientific method temporarily distracted them from their inquiry.
Distracting excerpt 1: “We need variables”

While it is ambiguous whether the attention on “variables” in the opening scenario helps or hinders the students’ inquiry, the continuation of this conversation makes it clear that talk of “variables” diverts rather than supports the students’ inquiry:

100. Leslie: Yeah, but then we’ll have two changing variables. We only need one.

101. Chris: You talk about (analysis?)?

102. Leslie: Like one variable has to change. (to Chris)

103. Chris: You talk about (analysis?)?

104. Kevin: Yeah, like one—the independent variable, the one that change. (To Chris, with certainty)

105. Leslie: Yeah, like one you change and two we keep the same. (with certainty)

106. Chris: Oh, got it.

107. Kevin: So one thing has to change.

108. Chris: Uhh…what other area?…let’s do the sidewalk.

109. Kevin: Sidewalk?

110. Leslie: There maybe something there, ‘cause like…

111. Chris: ‘Cause whenever it rains, it’s like—

112. Leslie: With every set of data, there’s going to be something that’s off the wall. So like…(inaudible), nothing you could get.

113. Kevin: Then why use it?

114. Leslie: (inaudible)

115. Chris: Like all the times when it rains, once—well when it rains, worms crawl up onto the sidewalk.

116. Leslie: That’s what I’m saying.

117. Kevin: So, let’s see…all right.

118. Leslie: So we could do the sidewalk…

Here the students correctly remember the relevant aspects of scientific method—that the “independent variable” is the “one that change[s]” (line 104) and that other
variables “we keep the same” (line 105). The problem, however, is that attending to such experimental considerations as a rigid requirement shifts their local goal to thinking of something to change and pauses their productive inquiry about earthworm habitats.

Between lines 101-107, the students mention four times that one variable is supposed to get changed. Responding to Leslie’s reminder in line 105 that the independent variable is the “one you change,” Kevin (line 107) says, “So one thing has to change.” Chris in line 108 continues the job of suggesting “what other area” they could choose, coming up with “the sidewalk.” Kevin asks, incredulously, “Sidewalk?” perhaps because an impenetrable chunk of concrete seems to be an unlikely habitat for earthworms. Chris and Leslie together justify the choice of sidewalk: worms crawl up there when it rains. And besides, “With every set of data, there’s going to be something off the wall…nothing you could get” (line 112). Kevin initially wonders why to choose an off the wall site that will yield problematic data: “Then why use it?” (line 113), but appears to accede to this line of reasoning after the same arguments get repeated. In summary, when taking up the challenge of looking for something “to change” — a challenge brought on by their consideration of “variables” — the students choose and defend investigating a site where earthworms could not live.

Our point isn’t that the students choose an implausible habitat to test, but rather, that the plausibility of this habitat is not an issue in their conversation. With the task of changing one variable — thinking of another test site — now their in-the-moment goal, the students make no effort to defend the plausibility of their choice but settle upon an “off the wall” test site where earthworms merely visit rather than live. With a sole focus on “variables,” the original goal of inquiring about the best earthworm habitats has faded
to the background, and the more productive line of inquiry suggested in line 99 (where they considered using a well-trodden site to test if earthworms are buried just beneath the surface) gets dropped.

Disputing our claim, one may argue that considering independent vs. dependent variables focuses students on the need to compare different sites (line 95), which can lead to productive inquiry later in the discussion once they get past “the sidewalk.” However, the students had already addressed the need to compare sites, repeatedly, before “variables” entered the conversation. Examples include comparing the top and bottom of a hill where run-off collects (see the Causal Explanation section above) and comparing wet vs. dry habitats, in buckets and in situ (see Scientific Argumentation). It is therefore unreasonable to credit the talk of “variables” with alerting students to the need to compare sites.

One may also point to evidence of inquiry in the sidewalk discussion; the students argued, and hinted at a causal explanation of why earthworms appear on sidewalks after rain. But not all argumentation and mechanistic reasoning constitute inquiry, which we defined as the pursuit of coherent, mechanistic accounts of natural phenomena. As emphasized above, the argument about whether it is OK to choose an “off the wall” site to fulfill the task of finding “one thing…to change” is an argument about what is allowed on school assignments, not an argument about the suitability of potential earthworm habitats and how to test them. Furthermore, the implied mechanistic reasoning, that rain wets the soil so much that earthworms crawl onto the sidewalk to avoid drowning, is offered in the service of defending the “off the wall” choice of sidewalk as a place to test for worms — even though worms don’t live there. To be fair, that piece of causal
reasoning could contribute to inquiry about another issue, such as whether earthworms breathe air, but here it is disconnected from the students’ ongoing productive inquiry about the best habitats for worms. In summary, although focusing on “variables” didn’t stamp out all good reasoning from the discussion, it temporarily distracted students’ from the particular ongoing inquiry in which they had been productively engaged.

_Distracting excerpt 2: “My teacher was very, very, very, very precise”_

A while after the sidewalk incident (the opening scenario), explicit talk of the scientific method entered the small-group discussion for the second and final time:

321. Kevin: Does the moisture increase if pollution decreases? Well, I don’t think we’re really able to test it.
322. Chris: And the texture of the soil is softer.
323. Kevin: That’s like more than one hypothesis. We can only have one.
324. Chris: Yeah, but there can be more than one variable.
325. Kevin: There can be more than one variable but not more than one hypothesis.
326. Chris: This is the independent and this is the dependent.
327. Kevin: Then why are you putting it in your hypothesis?
328. Chris: Dependent depends on the independent.
329. Kevin: But why are you putting it in your hypothesis? Why are you putting in your hypothesis?
330. Chris: You have to put all the variables in the hypothesis; otherwise it’s not a valid hypothesis. I know this because I was in GT science and my teacher was very, very, very precise.
331. Kevin: Ok.

The students here begin by thinking about possible relationships between soil pollution level, soil moisture content, and soil texture, and whether these links are testable (lines 321-322). However, the conversation went in a different direction in line 323, when Kevin said “we can only have one” hypothesis. He appeared to view the group’s ideas as consisting of two hypotheses, i.e., _if pollution decreases, moisture_

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3 Short for “Gifted and Talented,” a label the school systems in the State use for students who test into a particular track for academic subjects, including science.
increases, and if moisture increases, the soil gets softer. Chris responded that a hypothesis can contain more than one variable; he may have viewed the hypothesis under discussion as if the pollution decreases, the moisture level increases and the texture gets softer. This argument between Chris and Kevin was not about plausible causal links among pollution, moisture, etc., and how to test them, but rather, about the form in which they were permitted to express their ideas in school science. Furthermore, the argument ended not with an appeal to coherence or evidence from the natural world, but with an appeal to authority, Chris’s “very precise” teacher from a previous year (line 330). This was not surprising, given that the scientific method is often taught as disconnected steps to be memorized rather than constructs rooted in and connected to sense-making. (See the review of the scientific method section.) In short, the argument over the form of a valid hypothesis temporarily distracted students from inquiring into the links between pollution, moisture, and soil texture, and how to test them.

After Ms. Jones briefly checked in on their progress, the students resumed that inquiry. They ended their group brainstorming agreeing on this hypothesis: “As the moisture and health of the soil increases and the soil is softer then the number of earthworms will increase because earthworms like damp, moist, dark, soft and healthy soil.” Although this statement did not conform to the definition of “hypothesis” appearing on the HSA, which is limited to one independent variable and one dependent variable, it suggested productive inquiry in that it (i) made a prediction about how the size of earthworm population (the dependent variable) would depend on soil features (independent variables), (ii) showed awareness that multiple variables are needed to characterize a habitat, and (iii) suggested attention to casual relations.
In summary, any confusion students had about the terms associated with the formulaic scientific method did not prevent them from performing genuine scientific inquiry. On the contrary, when their activity became decoding or following those rules, it drew students’ attention away from the productive inquiry they were doing.

When goals collide, part 2: Teacher attention

During a project meeting, when Ms. Jones shared video and transcript from the brainstorming activity with a cohort of eight high school environmental science teachers from same county and adjacent city, teachers immediately zeroed in on the two “scientific talk” excerpts. Examples of comments included:

“So there're two areas where they spend a little bit of time with independent variables (referring to the two excerpts students talked about variables and hypothesis), what exactly those variables are, and the roles that they play. But in the end, they have like you know they're covering everything in the end (referring to the students’ hypothesis at the end). So it's very clear that they're sort of aware of variables, that variables play a role, but not quite exactly sure what that role is.”

“This is science! Bottom line is that you CAN’T have everything. So you have to start picking and choosing. And then you do one test and then where do you go from that test. And that's, you know, that's something I struggle with in my own instruction because of our shortness of time and everything. It's very easy to fall into the trap that, OK we did this and this is what we found and that's that. But that's not really how science works. So you sort of narrow down your problem. You try and figure out how to define it. And figure out an investigation, design an investigation, that somehow addresses that, and what do you learn from that, and where do you go next. So they're identifying like all possibilities. When it actually comes down to refining it, I hear them struggling with how are they going to refine, refine it.”

These comments represented the teacher group’s two major concerns: 1) putting everything in one hypothesis showed that the students did not understand the role of
variables; 2) students had trouble picking through these variables to “narrow the problem down.” The elements of productive inquiry we saw in the students’ discourse — scientific argumentation, causal reasoning, attending to confounding causal factors, attending to data reliability — were overlooked in this discussion. Also, as we suggested above, the multi-variable hypothesis students made at the end made sense in the context of ecological field work, where a given habitat must be characterized by multiple factors that cannot always be independently controlled. The teachers, however, agreed that this attempt to look at many factors at once was a common problem that would “trap” the students. They identified this tendency as going against the normal requirement of scientific investigation (“you do one test and then where do you go from that test”), which made it “challengeable” to implement open-ended, project based instruction.

Even assuming the students need to refine their understanding of variables, however, the teachers’ “deficit” diagnosis does not take into account the evidence that the students, when not using the word “variables,” show at least a partial understanding of the need and the underlying purpose of controlling variables and teasing apart confounding causal factors. Furthermore, as mentioned above, the teachers do not show evidence of noticing the numerous other productive aspects of inquiry in which the students engage. In brief, the teachers focused their attention on the aspects of the students’ reasoning involving explicit mention of “scientific method” vocabulary, to the exclusion of students’ tacit use of variables and other aspects of the students’ scientific inquiry.

According to Herbst & Chazan (2003), opinions articulated by teachers within groups of colleagues often indicate the unspoken norms for the group. For these teachers,
our data suggests it was a norm to attend disproportionately to students’ use of “variables” and to assess students’ performance at scientific inquiry on that basis.

In summary, at the individual and/or group level, the teachers’ attention to the correctness of students’ use of “variables,” a term enshrined in the scientific method, pulled their attention away from students’ tacit but productive use of variables and from other productive aspects of their scientific inquiry. Levin, Hammer, and Coffey (2009) argue that teachers’ focus of attention likely stems not just from their personal beliefs but (largely) from the historically determined way in which scientific inquiry and method are embedded in their local school systems.

Conclusions

Most critiques of a formulaic “scientific method” focus on the inadequacy of ordered steps as a description of scientific practice or as a guide to instruction (Conant, 1951; Lederman, 1998; Hodson, 1996; Wink, 2005; Windschitl, 2004). Our critique centers not on philosophical deficiencies, but on how students and teachers experience the “scientific method” in classroom and how the scientific method focus can affect students’ authentic scientific inquiry. First, we reproduced the results that scientific method is often taught as ordered steps and that students can engage in scientific inquiry using everyday language, showing no evidence of being guided by those steps. Then, we offered existence proofs that

- The scientific method, when viewed as rigid, decomposable steps, not only contributes little to scaffolding inquiry, but can also distract students and teacher away from attending to productive scientific inquiry.
When students pursue authentic scientific questions, the hypotheses and tests they develop can contribute to their investigations without necessarily obeying the requirements of “the” scientific method.

In short, teaching and learning the scientific method and engaging students in more authentic scientific inquiry can emerge as two distinct classroom objects that conflict. How did this disconnect develop?

We postulate that a productive approach towards teaching scientific inquiry would not begin by introducing students to decontextualized steps. Even the more sophisticated versions of scientific practice (NRC, 2007) risk artificially demarcating inquiry and undermining students’ scientific reasoning when set out in advance as a roadmap for student reasoning; students conducting an investigation may focus on following the roadmap rather than thinking their way toward the destination. We speculate that teachers should instead start by noticing, bringing out, and building upon the productive, sometimes nascent inquiry abilities that we and others have observed in students. Instruction can eventually help students identify steps and introduce vocabulary terms such as “variables” as formalizations of thought processes the students have actually experienced. By contrast, as Ms. Jones’ students’ illustrated, when articulated categories of scientific process are not rooted in and built on what students are doing, they risk undermining reasoning, distracting students and teachers from the very activities we’re trying to foster.

References:


*Science Education, 79* (4), 393-413.


