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Helping students make meaning of authentic investigations: findings from a student–teacher–scientist partnership

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Abstract

As student–teacher–scientist partnerships become more widespread, there is a need for research to understand the roles assumed by scientists and teachers as they interact with students in general and in inquiry learning environments in particular. Although teacher roles during inquiry learning have been studied, there is a paucity of research about the roles that scientists assume in their interactions with students. Socio-cultural perspectives on learning emphasize social interaction as a means for students to make meaning of scientific ideas. Thus, this naturalistic study of classroom discourse aims to explore the ways scientists and teachers help high school students make meaning during authentic inquiry investigations. Conversational analysis is conducted of video recordings of discussions between students and teachers and students and scientists from two instances of a student–teacher–scientist partnership program. A social semiotic analytic framework is used to interpret the actions of scientists and teachers. The results indicate a range of common and distinct roles for scientists and teachers with respect to the conceptual, social, pedagogical, and epistemological aspects of meaning making. While scientists provided conceptual and epistemological support related to their scientific expertise, such as explaining scientific phenomena or aspects of the nature of science, teachers played a critical role in ensuring students' access to this knowledge. The results have implications for managing the division of labor between scientists and teachers in partnership programs.

Keywords

Meaning making; Inquiry; High school; Scientists; Social semiotics

A number of programmatic (e.g., Spencer et al. 1998) and systemic efforts (e.g., National Science Foundation's Graduate STEM Fellows in K-12 Education program) have involved scientists in classroom activities. Despite scientists' increasing involvement in K-12 education, there is a paucity of research on the roles of scientists in classrooms. Most research examining scientists' involvement in classrooms has examined gains in student achievement (Laursen et al. 2007) or interest in science (cf. Sadler et al. 2010), rather than the unique ways that scientists, who are trained to make meaning of scientific information, can help students to do so. In addition, although there has been a fair amount of research investigating the ways teachers help students make meaning (Mortimer and Scott 2003), the roles teachers assume in student–teacher–scientist partnerships has not been a focus of study. Our research aims to shed light on scientists' and teachers' roles in helping students

make meaning of scientific investigations in the context of a student–teacher–scientist partnership.

Student–teacher–scientist partnership in an authentic science environment

The partnership studied here engages students in the design, conduct, and interpretation of authentic science investigations with mentorship from teachers and scientists. We use this context to characterize the acts of teachers and scientists because of the particular opportunities and challenges that authentic investigations present for students as they make meaning. Authentic science learning is commonly thought to involve students in practices resembling those of scientists, such as asking scientific questions, designing and conducting research, generating and testing hypotheses, and communicating results (National Research Council 2000). Authentic science learning is also characterized by students' ownership of the research problem, their epistemic authority in determining how the problem will be addressed (e.g., designing the research, selecting variables, choosing methods for collecting, analyzing, and representing data, etc.), and the complexity of their reasoning as they interpret results (Chinn and Malhotra 2002).

Learning environments are often characterized as authentic to the extent that they engage learners in real-world, situated activity (Lave and Wenger 1991). Theories of situated cognition and cognitive apprenticeship offer explanations for how interactions between experts and novices offer access to “participation in socially organized practices, through which specialized local knowledge, rituals, practices, and vocabulary are developed” (Hennessy 1993, p. 2). Situated cognition establishes learning as a social activity where learners develop the knowledge, skills, language, and customs of a discipline through interacting with other members of the discipline including peers and experts (Lave and Wenger 1991). Cognitive apprenticeship refers to the processes and experiences through which novices develop cognitive skills required to perform in a certain discipline as they work closely with experts (Collins 2006). The learning experience studied here was designed as an operationalization of these theories and with features of authentic learning environments in mind (Dolan and Grady 2010). Thus, our purpose in this study was to examine how teachers and scientists as experts act to facilitate meaning making by students as novices.

We define meaning making as the use of language and other semiotic resources to understand and interpret the outside world, including its living, physical, and social phenomena. By using the analytical tools of social semiotics to interpret meaning making acts (Lemke 1998), we sought answers to the following research questions: (1) What are the specific expert (i.e., teacher and scientist) acts that facilitate novices' meaning making? (2) What functions do these acts serve in the meaning making process? and (3) What are the differences, if any, between teachers' and scientists' meaning making acts?

Social semiotics of teachers' and scientists' acts

Sociocultural perspectives on learning view meaning making as learners' internalization of ideas that are available on a social plane, where interaction and discussion can take place (Mortimer and Scott 2003). Teachers assist learners in making meaning of ideas through discourse, for example, by questioning, offering feedback, or providing structures for thinking (Tharp 1993), as well as by shaping, selecting, or marking ideas (Mortimer and Scott 2003). From these interactions, learners are expected to develop personal meanings of ideas, concepts, or phenomena that are then internalized (Vygotsky 1978). Thus, we chose to focus on primarily on spoken dialogue between teachers and scientists as experts and students as novices to identify experts' acts that help novices make meaning of their investigations.

We used a social semiotic framework to interpret the functions of teachers' and scientists' meaning making acts. The discipline of social semiotics aims to understand the ways people make meaning by ascribing interpretations to people's actions as they act and interact within social groups (Lemke 1990). Actions and objects do not have fixed meanings, rather individuals make meaning of them as they experience them. Individuals use a variety of semiotic resources (e.g., language, gestures, symbols) to make meanings, and communities develop semiotic formations by using these resources in a consistent and systematic way (e.g., scientific questioning). In our analysis, we focus primarily on how scientists and teachers use linguistic and visual resources to help students make meaning of authentic investigations.

Lemke (1998) argues that meaning making happens through three main semiotic functions: presentational, orientational, and organizational. Jaipal (2010) described these functions in a teaching context, and renamed them conceptual, social, and pedagogical, respectively. Individuals, as readers or listeners, first ascribe meaning to participants and processes (i.e., answers to questions of what, who, where, when, or how); this refers to the presentational or conceptual function. Individuals then establish a relationship between themselves and the producer of the text or speech, which is the orientational or social function. The reader or listener assigns roles and statuses to participants in the communicative event, and makes judgments about the events and personalities (e.g., good versus bad, friendly versus hostile). Finally, individuals identify the wholes, parts, and order of the semiotic components, which refers to the organizational or pedagogical function. Jaipal (2010) also described an epistemological function, which refers to acts indicative of the nature of knowledge.

In our analysis, we used Jaipal's terminology because it is more descriptive of teaching situations. Specifically, we characterized scientists' and teachers' acts as: (1) *Conceptual* acts that aimed to increase students' conceptual understanding of the phenomena, such as providing explanations or information; (2) *Social* acts that indicated the experts' position as a knowledge authority, such as confirming students ideas or invoking new ideas; (3) *Pedagogical* acts that aimed to organize students' ideas visually or verbally or increase students' access to knowledge; and (4) *Epistemological* acts that offered ways of knowing, such as providing analogies or confirming or explaining aspects of nature of science.

Methodology

We conducted a conversational analysis of “naturally occurring discourse” (Macbeth 2003, p. 246) to examine in-depth the practices of scientists and teachers as they helped learners make meaning of their investigations. Data sources included video recordings of classroom activities, interviews with teachers and scientists, and student work. We employed purposeful and convenience sampling to identify geographically practical research sites (Patton 1990) to ensure that teachers' and scientists' acts, primarily their talk, could be observed throughout the students' investigations. Although we primarily report video data here, interview data helped us to understand teachers' and scientists' intentions behind their actions and student work provided a richer context for interpreting some of the interactions between students and experts.

Program context

The context for this research was the Partnership for Research and Education in Plants (PREP). Although PREP as an inquiry learning context is described in 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 one of the project staff explains to students that their assistance is needed in characterizing the functions of genes in the plant, *Arabidopsis thaliana*. Students are familiar with the idea that genes help determine

characteristics, but usually only visible characteristics such as height or color. Students 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 eight-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 make comparisons between wild-type and mutant plants and between treated and untreated (i.e., control) plants in order to draw conclusions about the impact of disabling genes on the plants' responses. Students end by sharing their results and conclusions with their partner scientists, who ask questions about their findings and explain how they see the students' results fit into what is known in the field.

Participants

Data were collected from three classes of two teachers in two high schools in the mid-Atlantic region of the United States. All names are pseudonyms and, for readability, pseudonyms starting with "S" are used for the scientists and with "T" for the teachers. Trisha, a Caucasian female with 8 years of teaching experience, taught at a specialty public school with a curricular emphasis on science, technology, and mathematics. Although this school was located in an urban setting, it enrolled students from both rural and urban areas based on their academic achievement. Trisha had certification in biology teaching, a master's degree in life sciences, and 2 years of experience implementing PREP prior to her participation in this study. One of Trisha's classes was included in this study, which enrolled 16 students who were mostly 11th graders. Ted, a Caucasian male, taught in a rural public school. Ted had more than 10 years of teaching experience, certifications in biology and chemistry teaching, and 1 year of experience of implementing PREP. Two of Ted's classes participated in the study, each enrolling twenty-four 9th and 10th grade students who represented a broad range of achievement levels. In all classes, students worked in pairs to design and conduct their PREP investigations.

Susan and Sandy, two Caucasian female scientists, partnered with Trisha and Ted, respectively. Both scientists studied *Arabidopsis*, the organism used in PREP investigations, in their research, and had led their research groups more than 10 years. The scientists provided the wild-type and mutant plant seeds as well as information about the particular genes that had been disabled in the mutants. The scientists also visited with students for an extended class period toward the end of the students' eight-week long investigations. These visits were the first and only opportunities for face-to-face interactions during the investigations. During the class visits, scientists engaged in one-on-one discussions with student groups about the design and conduct of their investigations, as well as their results, interpretations, conclusions, and recommendations for further research. During the small group interactions between scientists and students, other students in the class were taking care of their plants, making observations, or collecting and analyzing their plant data, unless their attention was specifically requested. Several groups of students, particularly in Ted's class, employed the same treatment in their investigations (e.g., salt). In these instances, the scientist engaged in discussion with multiple student groups at the same time to allow for comparison of results across groups.

Scientists provided additional assistance via email, their own research group websites, the PREP program website, and short video-recorded descriptions of their research, which were played for students at the outset of their investigations. These resources made additional information available to students about scientists' research and the design and conduct of

PREP investigations, but were not included as data in this study, as they did not present opportunities for dialogue between students and scientists.

Data sources and analysis

Student–teacher and student–scientist interactions were captured through video recordings made by the second author and a graduate assistant. Video cameras and microphones were placed strategically to record as much of the naturally occurring classroom discourse as possible, including whole class and small group discussions. The backstage camera was switched between the whole class microphone and a student table microphone as needed to record whole class or small group discussion. Each class was recorded five times during their PREP investigations (15 class sessions total), yielding 45 videos of 45–90 min in duration.

Conversations were then analyzed using the manifest content approach (Erickson 2006). In this approach, the focus of the analysis is the subject of interest, in our case the verbal actions of teachers and scientists, rather than any latent content. An initial set of codes was developed by the first author, who reviewed all videos, selected two (one per teacher) in which frequent and diverse interactions were observed between students and scientists or teachers, and used these videos to develop a preliminary code list of teacher and scientist acts. This list was used by the two authors and a graduate assistant to independently code several video segments. The assigned codes were discussed and conflicts were resolved by re-naming, re-defining, dividing, merging, or generating codes. By using the final list of codes presented on Table 1, each researcher independently coded one of the three videos of the same classroom period and discussed the assigned codes in 60–90 min roundtable meetings. During the meetings, each researcher presented segments that s/he had difficulty in coding, and conflicting points were resolved through discussion. Since the researchers watched videos of same class period captured from different angles, there were overlapping scenes that reinforced code assignments. In addition, the first author checked coding across all raters using a random subset of video segments to ensure that the codes were applied consistently.

Once all videos were coded, we used a social semiotic framework (Jaipal 2010) to organize the empirically derived codes based on their functions. First, we independently grouped the codes by using the social semiotic framework. Then we compared the grouping schemes that we created individually to reach consensus. The social semiotic framework was sufficiently broad to encompass the all of the expert acts that we identified during our analysis. Yet, we were only able to characterize teachers' and scientists' actions fully if we considered multiple semiotic functions simultaneously, rather than trying to fit their actions into single discrete categories of the framework. In other words, our analysis resulted in the identification of actions with dual functions.

Quotes from coded video segments were transcribed and are included verbatim. The actions described here were primarily observed during student–teacher and student–scientist dialogues regarding interpretation of students' data near the end of their investigations. By examining experts' actions in video rather than transcripts, we were able to identify and characterize actions with physical elements, such as drawing diagrams, organizing and reorganizing pots of plants, or making pen marks that drew students' attention to particular data points. In addition, by analyzing video data, we were able to identify referents during spoken discourse, such as which plants were being compared when students said, “these are greener” or “these are taller.”

Quality standards

We utilized several strategies to establish the credibility, transferability, dependability, and confirmability of our analyses and results (Anfara et al. 2002). We aimed to establish credibility of our findings through prolonged engagement in the field. For example, by observing and making multiple, simultaneous video recordings of the participating classrooms, we developed our own familiarity with each classroom context and its culture. We had formed comfortable and collegial relationships with the participating teachers and scientists, who had been involved in PREP prior to their involvement in the study. This helped ensure our understanding of the teachers' and scientists' views of and priorities for their PREP involvement, and ensure that a level of trust had developed that would support honest and reflective discussion of their actions in the classroom.

We aimed to ensure transferability of our findings by sampling purposively and developing rich descriptions of the research settings. Specifically, by analyzing video recordings, we were also able to make meaning of particular actions and generate richer description. For example, as noted above, video recordings enabled us to identify referents, such as when the teachers or scientists asked students, "What about those?" when referring to particular plants or data points. Video recordings also enabled us to characterize actions with physical elements, such as when teachers, scientists, or students organized or reorganized pots of plants. Through the process of video recording, we also aimed to capture the full range of teacher and scientist actions and their interactions with students. We purposively selected two distinct classrooms contexts to increase the likelihood that we would observe as broader range of teacher and scientist actions.

We aimed to establish credibility and dependability of our data analysis through peer debriefing and by confirming assignment of codes across multiple coders. Specifically, we checked overlapping scenes as well as a random subset of video segments for consistency in our code assignments. We also discussed our independent coding of all of the videos during roundtable meetings during which each researcher presented segments that s/he had difficulty in coding and the researchers reached consensus regarding how to code these segments through discussion. Only the codes for which we reached full consensus are reported here.

We aimed to establish credibility of our data analysis through triangulation and member checking. We cross-checked our interpretations of the video recordings with teacher and scientist interview data and with student work. For example, Ted assisted his students in making meaningful comparisons of their data by prompting them to make pen marks that distinguished the particular comparisons they were making. We observed Ted repeating this action as he made his way around the classroom, working with each small group. We identified how students responded to his prompting by reviewing video segments and student work. During an interview, Ted explained that his intention was to assist students in organizing their data. This interview served as a "member check," in which our independent interpretation of Ted's action could be corroborated by his explanation.

Finally, we aimed to establish confirmability of our findings by reflecting on and articulating the limitations of the research, which we explain in our concluding comments.

Results

Scientists and teachers used a series of strategies to support students in making meaning during their investigations, which are categorized according to their semiotic functions in Table 1. Actions with dual functions are listed twice and noted with an asterisk. We start here with a dialogue between Susan and two students that includes numerous examples of

expert acts. This excerpt also captures the dynamic of expert-novice interaction in which the expert maneuvers the direction of the dialogue by providing information, anecdotes, or interpretations that are relevant to students' current experience.

This dialogue provides a glimpse into the many ways the teachers and scientists in this study helped students make meaning of their data and of scientific inquiry in general. In the following sections we will describe and illustrate how these acts take place.

Conceptual function of meaning making

Teachers and scientists aimed to increase students' understanding of concepts so that they were better positioned to make meaning of their experimental results. They enacted this conceptual function by explaining phenomena, providing information, interpreting results, and invoking new ideas. Teachers' and scientists' explaining acts were typically short and spontaneous. For instance, students working with Sandy had compared several characteristics of their plants, including bolt height, number and size of siliques (i.e., seedpods), and number of open flowers, but they struggled to synthesize their data to draw conclusions about the growth patterns of wild-type versus mutant plants. Sandy asked them about the color of their plants' leaves, and then explained why this comparison fit with their other data:

Sandy: What about the color of the leaves?

Students: These are greener (pointing to wild-type plants).

Sandy: I think these (mutants) are further along in their development (pointing to the plants). That is senescence associated with the discoloration of leaf and that is supported by lack of flowers. So, I think the one difference you guys found here is the difference in the timeline of development, which actually supports what you said. You saw that difference early on (referring to faster growth of mutant plants initially).

Teachers and scientists also acted to extend students' knowledge by providing timely and relevant information for students to consider. For example, Susan talked with students who tested the effect of red light on plants with alterations in a gene important for flavonoid biosynthesis. In response to a question about other wavelengths of light that may be important for plants, one student said "probably the green one," and another said, "I think blue is important." Susan responded, "That is true! It turns out that flavonoid genes are particularly responsive to blue light. There are papers about this. They actually dissected what wavelengths the genes are responsive to." Susan then encouraged these students to do a similar experiment using blue light.

Teachers and scientists also provided information by explaining scientific terminology. Most students were unfamiliar with terms used to describe anatomical structures of the plants, such as bolt and rosette. Similarly, many students were unfamiliar with the term "seedpod," and even less familiar with its scientific name, "silique." Gaps in students' knowledge limited their ability to communicate with one another and the scientists. In the following example, students from different groups discussed what they were supposed to measure about the seedpods. Although Ted pointed out what seedpods were in the previous lesson, not all of the students' plants had developed seedpods. When Ted realized that some groups were not sure what seedpods were, he explained the meaning of the term to the whole class.

Student 1: The bolts are those big long things.

Student 2: I get that! Do you call those things pods?

Student 1: I don't know what the hell pods are.

Student 2: Pods? It is pod.

Student 1: PoD, poD (emphasizing the D at the end of the word).

Student 3: These are the pods. It is like there are thousands of them (walking by and pointing to the pods on the bolt).

Example dialogue

Speaker	Dialogue	Act	Function
Susan	Interesting (examines plants). Experimentals and these two are controls (arranges plants). Okay, that is nice. Cool. Alright, what do you see? You said there is not much difference	Confirming	Social, Epistemological
Student 1	There is not much difference between the experimental and control groups but, like we have a lot more plants actually germinate in the mutant than in the wild-types		
Susan	That seems to be kind of the recurring theme around here	Referring to other's data	Social, Epistemological
	So this is one way to do this right? Put the mutants over here, and in general your wild types do look different from those guys	Interpreting results	Conceptual, Social
	And visually I agree that, now you do this, experimental (separating experimental plants and control plants—that does not look very different from that. Just by looking at them. Then what are you measuring, I guess, is the question. To try to —	Confirming	Social, Epistemological
Student 1	So far we have been measuring bolt (i.e., stem) height, once they started sprouting the number of buds on average, and the number of flowers on average, per plant. And I guess we haven't seen any, very much fruit yet. So we have		

	not sort of started measuring them yet. But so far—		
Susan	They are not very prolific are they?	Interpreting results	Conceptual, Social
Student 1	Not yet		
Susan	Huh, interesting. Well the cool thing is that you can sometimes measure stuff and see differences you don't see by eye, right? So, that is—I am not sure that is going to happen but—	Explaining an aspect of the nature of science	Epistemological
Student 1	It might		
Susan	It does work out sometimes. It is very nice to do those kind of things that are not immediately obvious to us as human beings. So, for how long did you treat them?	Explaining an aspect of the nature of science	Epistemological
Student 2	It depended. We started out like, just like during the class treatments, but on accident we left them in there overnight and we saw that, that the <i>Arabidopsis</i> were really depleted and recently we left in them over weekend they were really (pause)		
Student 1	They didn't look very good		
Susan	Was there difference between the refrigerator and the cabinet?		
Student 2	Umm, we have pictures. We can take a look		
Susan	Because that sounds like an interesting experiment. Sometimes the best stuff comes out of serendipity right? That you happen to do something you did not intend to do and all of the sudden you see something cool. That is fine	Explaining an aspect of the nature of science	Epistemological
Steve ^a	What would you expect would		

	happen in the plant in the cold? What would be different?			
Student 2	Well, didn't we see that the refrigerator has more moisture in the soil?			
Student 1	Yes, that's because less evaporated out or maybe because the plants were metabolizing more slowly			
Susan	Yeah, but that could work towards, to the advantage of the plant, right? The ones put in cold might do better in the dark, over the weekend. Maybe. That is a hypothesis	Invoking a new idea		Conceptual, Social
	<i>Arabidopsis</i> kind of likes the cold, so, more than the heat. It is probably not perfectly happy growing at 4°, but it is at least tolerant, I know	Providing information	Anthropomorphizing	Conceptual, Social, Pedagogical
	Talking about serendipity, we have actually taken seeds, and put them on filter papers, and put them in fridge with the idea that we were going to plant them; and then we completely forgot about them for months. And you go back and they germinated in the refrigerator. They're white, you know, but still, I was like, "I didn't expect that"	Explaining an aspect of the nature of science		Epistemological

^aSteve is a project staff member

Ted: Remember, the number of pods in each plant divided by number of plants. (A few minutes later, after realizing some groups do not understand what a seedpod is) Hey, the pods, these are seedpods, there are seeds inside those.

Ted made the idea of seedpods relevant to students by relating it to a more familiar idea: pod as a container. Wickman and Östman (2002) call this a "stand fast," or a familiar item or idea to which a relation is made to close a gap in knowledge. Other examples of technical terms that teachers and scientists defined during discourse with students included lesion, senescence, and necrosis.

Teachers and scientists acted to extend students' knowledge by offering their own interpretations of students' results. For example, Susan offered her own interpretation of students' results in the opening dialogue by saying, "They are not very prolific, are they? Huh, interesting." Ted commented on one group's plants, "This group's wild-type control seems to be brighter green than its mutant control. Is that the case for anybody else or not?" Examples of this sort were common in all classes. By offering interpretations, experts either solidified students' interpretations or brought to light new interpretations that students had not yet considered.

Teachers and scientists also acted to expand students' conceptual understanding by invoking new ideas, including introducing different interpretations, suggesting alternative explanations, or noting confounding factors that students had not yet verbalized. For example, in the opening dialogue, Susan pointed out that the coldness of the refrigerator might slow the plant's metabolism enough to help it survive lack of light. Ted also invoked a new idea during a dialogue with students who used salt as their treatment and concluded that, in general, their mutant plants grew "better and faster" than wild types. Ted then asked these students why the absence of a gene might enable plants to grow faster:

Ted: So that gene may somehow normally slow the growth, when it is in the wild types.
Student: Possibly.

Ted: Why would it be a benefit, the slow growth, I wonder? I mean, maybe, the gene does not necessarily help. I mean, maybe slow growth may not be helpful. The wild type has the genes normal, the mutants have the disabled gene. They (the mutants) grow faster, maybe a little bit healthier... So I wonder when that gene is active in the normal, in the wild types, might it be better for some reason, under some certain circumstances to grow slower?

Social function of meaning making

Teachers and scientists enacted the social function of meaning making in two main ways: presenting themselves as knowledge authorities and promoting the idea of scientific community.

Playing the role of knowledge authority—Experts assumed the role of knowledge authority by confirming students' ideas, providing information and explanations, interpreting results, and invoking new ideas. Their enactment of conceptual functions positioned them as knowledge authorities because their explanations and interpretations reflected their expert knowledge. By confirming, teachers and scientists signified their approval of students' results or interpretations. Some confirming acts took the form of encouragement, in which the experts praised students' work and encouraged them to continue their investigations as planned, for example: "I am glad to have such exciting data" (Trisha), and "I would really like to follow up on this because this is exactly the kind of thing we hope to get out of this kind of research" (Susan). In other cases, confirmation came before students engaged in a particular activity:

Ted: Look at your bolts and tell what else we can collect data on?

Student: How about those little things on it (pointing to flowers)?

Ted: What things? Flowers? Yup, certainly, that is something you can measure.

Other confirming acts were more generic and prevalent. These appeared to be part of a social dynamic that kept students talking and the dialogue moving, for example: "I see what you mean," or "Okay, that is good."

Promoting the idea of scientific community—Teachers' and scientists' acts created social meaning by establishing a common understanding of terms, concepts, and practices, as well as by referring to others' results and by using scientific terminology in ways that encouraged students' use of terminology. These actions implied that science is a social practice in which members of the practice community develop common understandings of the standards, notions, and practices of the discipline. Specifically, scientists come to agreement on the use of particular terms to ease communication within the scientific community, and scientists refer to one another's work to confirm their own findings or place them in a larger conceptual context.

Ted in particular acted at several points to establish common understandings in his classes. For example, he made substantial effort to establish a common understanding about how to make measurements in order to produce data that students could compare across groups. Unlike Trisha's class, where each group had freedom to select their own treatments, Ted's students had to choose one of the two possible treatments, which were narrowed down through voting on a list of student-generated choices. Ted saw this as means for combining data across groups to generate a larger data set that would allow for more robust analysis and interpretation. As a result, he and his students had to make sure that they approached data collection in a consistent and reproducible way. The following example demonstrates how Ted went about this:

Ted: Let me ask you something. Could this be a problem? If Julie always records data on the wild types and Lisa always record data for the mutants?

Student 1: Yes

Ted: Could it be problem?

Student 2: No.

Ted: No, it couldn't be a problem? I don't know I am asking you.

Students: (Mumble, no clear response).

Student 3: If they measure differently and then they will be getting different results.

Ted: What if we say one time Julie is going to do these two (wild types) and Lisa is going to do these two (mutants), could that be a problem?

Students: (Mixed responses of yes and no.)

Ted: I don't know, I am asking you. Can there be a problem with measuring if Julie measures the mutants today and Lisa measures the wild types today, but on Wednesday Lisa measures the wild types and Lisa measures the mutants? Can that be a problem? Does that cause any sort of difficulties?

Student 4: No

Ted: Okay. No? These are the things you may want to be aware of. You may want to communicate each other about how you measure. Hey, what if I bring all of these, the data that all the salt people working on, if I kind of lump all that together, which I will do. Each group has got a worksheet on the Excel spreadsheet and there is a totals page. What if this group measures different than that group? I mean, would that be a problem?

Ted also stressed the importance of finding common ways to measure before students recorded data that could be measured in multiple, valid ways. He explained that there could be ambiguity regarding what and how to measure, but the ambiguity is not a concern if the group reached consensus on an approach:

Ted: So, we know how we do leaves. We are counting them, okay? Umm, what if there is kind of like a little itty bitty leaf growing? Does anyone have just a little leaf starting to grow here (showing a sprouting leaf in one of the pots)?

Students: (Some say that they have little leaves starting to grow.)

Ted: Do we want to count them as a leaf or not?

Student: I count them!

Ted: Okay, good. We count them as leaf. I just want to make sure if someone is counting them as leaf, somebody else is using the same method, right?

Referring to others' data was another expert act that promoted the idea of scientific community. Teachers and scientists drew students' attention to each other's data by pointing out similarities in observations from different student groups or by seeking students' thoughts about whether their results were similar across groups. In this example, Ted segued from discussing observations with one student to query other groups to see if their observations were similar:

Ted: Hey (he calls for attention from the class and then refers to the student with whom he examining plants)—she says that her experimentals, and I can see what she's saying, are a little bit brighter green than her controls. Is that the case with yours or not, do you think?

Student 2: No.

Ted: You don't notice it?

Student 3: Yeah.

Ted: Do you? (Turning to the third group.)

Student 3: This is a little brighter.

Ted: But what about the other ones? The other experimentals. Put your two experimentals together and your two controls together, and compare them.

Student 3: Yeah, I see that the mutant experimentals look a lot lighter than...

Experts enacted the social function of shared language in their regular use of scientific terminology. By frequently employing terms such as control group, experimental group, dependent variable, independent variable, unintended variable, treatment, reproducibility, sample size, comparison, error bar, etc., experts infused the language of controlled experimentation into the classroom discourse. As seen in the preceding quotes, students incorporated at least some of these terms (e.g., control group, experimental group) in their dialogue with experts and peers.

Pedagogical function of meaning making

Teachers and scientists enacted pedagogical functions of meaning making by organizing students' ideas, increasing accessibility of knowledge, and checking students' knowledge.

Organizing students' ideas—Teachers and scientists organized students' ideas visually by using diagrams and lists, and verbally by summarizing. For example, Trisha drew line diagrams on the classroom whiteboard to illustrate the triggering effect of a stressor on a gene's expression and how changes in expression might manifest in a plant's phenotype. She also listed students' ideas for data collection on the whiteboard as students shared their plans during whole class discussions. Similarly, Ted used diagrams to explain why to calculate averages and illustrate how to design a method for recording data that would enable students

to make meaningful comparisons. Teachers and scientists also organized knowledge by periodically recapitulating key points from small group or whole class discussions. For example, Ted indicated the salient features of data recording by writing on the board as students made suggestions during a whole class discussion. He drew students' attention to information that is important to record by saying, "Okay, do you all see what I wrote here? I wrote today's date, I wrote total number of leaves, and you need to figure out the average by dividing the total number by the number of plants. Does that make sense?"

Increasing accessibility of knowledge—Teachers and scientists aimed to make knowledge intellectually more accessible to students by providing daily life explanations, using analogies, and anthropomorphizing biological phenomena. These acts offered new visual images of phenomena or connected new information with students' existing schemas. For instance, the following is a dialogue based on students' observations of brown spots on the leaves of their plants after treatment with ultraviolet (UV) light. Trisha initiated a whole class discussion after one group of students showed that they observed an increase over time in the number of brown spots on their plants' leaves.

Trisha: Does anybody else have brown dots on their plants? So a brown dot means what is happening to cells?

Students (chorus): They are dying.

Trisha: They are dying. Can UV radiation cause enough damage to cells to kill them?

Students (chorus): Yes

Trisha: Yes. Do all cells have light repair UV damage?

Student 1: No...

Student 2: Probably...

Trisha: Do we live in an environment with UV radiation?

Students (chorus): Yes.

Trisha: Do we evolve in an environment with UV radiation?

Students (chorus): Yes.

Trisha: Most of our cells have evolved mechanisms that repair UV damage.

Student 3: Not necessarily all of them!

Trisha: Exactly, right. If you are out there constantly exposing yourself to UV light, you are going to increase your—People get brown spots right?

Students (chorus): Yeah.

Trisha: I've got some I can show you (pointing to "age spots" on her own skin). I've got some blotches because that is also damage from UV light. So the dots represent the damage and I think it is really interesting here how wild-type experimental is sustaining some damage, but like John said, very similar to controls. This is very exciting.

In this excerpt, Trisha provided a daily life example of how UV light causes brown spots on human skin. In addition, she checked students' knowledge of related information.

Teachers and scientists also used analogies to increase the accessibility of scientific knowledge. Analogies appeared particularly helpful for explaining abstract concepts in genetics. In one class session, Trisha and her students watched a short video about how the mutant plants are generated, titled "How do you disable a gene?" A student expressed

confusion about how genes are transferred into plants, and Trisha responded with an analogy to plasmids and viruses.

Student: So they used the bacteria to change the, to insert the gene and we use plasmids?

Trisha: Right, so, if you are dealing with a bacterial cell, it is really easy to use plasmids, because those are genes that exist outside of the genome. But in this case they have to use a mechanism whereby the DNA can be inserted into plant genome. And since the *Agrobacterium* normally does that, that is kind of its job. You can kind of think it like, you know, how they tried to use viruses to deliver things to people, like to correct human diseases, although that did not work very well. Viruses—their job is to integrate their genome into our genome. It is kind of the same principle since we already have this mechanism to insert DNA, you can exploit it to get that DNA into the *Arabidopsis* chromosome.

Teachers and scientists increased the accessibility of scientific information by making anthropomorphic statements about the appearance or behavior of the *Arabidopsis* plants. Anthropomorphism refers to attributing human features (e.g., behavior, emotions, reasoning) to other organisms or non-living things. It has been argued that anthropomorphic statements can help learners understand scientific phenomena, with the caution that learners must be able to distinguish what is being anthropomorphized (Kallery and Psillos 2004). In the excerpt above, Trisha's description of the biological functions of viruses or *Agrobacteria* as “jobs” is anthropomorphic. Susan's statement that “*Arabidopsis* kind of likes the cold, more so than the heat” in the large opening dialogue is another example.

Checking students' knowledge—Teachers and scientists enacted the pedagogical function of meaning making by checking students' knowledge, primarily by questioning prior to delving deeper into discussion. Experts used knowledge checking as a means to review students' prior knowledge or prompt them to think about concepts and ideas related to the task at hand. For instance, in the following dialogue, Trisha probed students' understanding of bolting (i.e., stem growth), which led to additional discussion about the definition and interpretation of bolting.

Trisha: When the plant is bolting, what is it about to do?

Student 1: Reproduce.

Trisha: Does that necessarily mean it is growing better because it is happier?

Students: No.

Student 2: It could be stressed out.

Trisha: It could be stressed out, trying to reproduce before they die out. So the question is, are mutants handling the heat better or they are stressed and about to die?

Student 3: Wait, I have a question, I never heard of bolting before.

Trisha: So bolting is (pauses as she goes to the whiteboard).

Student 4: I might not have been here.

Trisha: [Drawing on the whiteboard.] So, you have your rosette leaves, and then they start growing the stem, this is the bolt, okay?

Trisha not only checked students' knowledge of the role of bolting in plant development, but also explained what the bolt is both visually and verbally. Ted checked students' understanding of concepts related to measurement, such as average, diameter, and unit

conversion, as well as of experimental logistics before students applied treatments or made measurements.

Epistemological function of meaning making

Teachers and scientists enacted the epistemological function of meaning making by offering students ways of knowing scientific ideas and explaining aspects of the nature of science.

Offering ways of knowing—Experts offered students ways of coming to know scientific ideas by confirming their ideas, providing daily life examples, providing analogies, and referring to others' results. Confirming acts, described as serving a social function above, helped students verify the validity of their experimental approaches and interpretations. Similarly, experts' use of analogies and daily life examples served a pedagogical function, described above, and an epistemological function, by making connections between what students already know and what they are trying to learn. For instance, the virus analogy described above offered students a way of thinking about the phenomenon based on what they had already learned in class.

As they made reference to others' data, experts also offered a way for students to think about their own results. For instance, Susan refers to another researcher's findings as she talks to students who used nickel sulfate as a treatment:

I'll see if I can dig up this paper... (Turns to another scientist) What we need to do is send some of these plants to [another scientist who studies ions in plants]. (Turns back to the students) So there is a guy who just came to [my university] who is basically just looking at these different mutants of *Arabidopsis*, looking for guys that have different ion levels including metals and things like this. None of [the mutants you are studying] are in his collection yet. He has not assayed those yet. I don't know that they are in the pipeline. If he is willing for you to just send seeds, it would be real interesting to see if, these are the ones we should look at (pointing to the students' plants), what happens when you treat them with nickel.

By referring to the publications and research programs of other scientists, Susan offers a new way for students to think about their results and their implications in a larger context.

Teachers and scientists also acted to help students make meaning of their experiments by emphasizing aspects of the nature of science (NOS). Experts brought two broad aspects of NOS, scientific methodology and sociocultural aspects of science, to students' attention. For example, in the opening dialogue, Susan explained the role of serendipity in science research in her response to students' unintentionally leaving their plants in the refrigerator. Other sociocultural aspects that experts emphasized included the socioeconomic impact of *Arabidopsis* research, differences in the way scientists from different disciplines approach problems (e.g., chemists vs. biologists), and disagreements among scientists. For example, Sandy prompted students to consider how results from their test of the effects of salt on a mutant plant could inform agricultural practices. Susan also addressed the interdisciplinary nature of science:

The fun thing about science is now that those disciplines are coming together. Chemists are starting think like a biologist and vice versa, and that is where it is really fun because you bring those two different cultures together. They are different cultures! I have a very close collaborator in a chemistry department. It has been 15 years now. She just thinks differently. It is fun because I can go to lab and say, "Did anybody see how pure this was?" For them pure is 90–95%, that is a great. For me, it is like, "Oh my gosh there is 5% impurity in there, you can't give it to a cell, you are going to kill it."

Experts' discussion of scientific methodologies included issues related to the quantification of observations, the risk of subjectivity in qualitative observations, the need for reproducibility, the importance of considering confounding or unintended variables, the value of larger sample sizes, the role of serendipity in scientific research, the idea that new hypotheses can be generated from results, and the need for model organisms in biological research. For example, Trisha indicated the importance of considering unintended variables when interpreting results by stating, "You might have had some unintended variables. It is important to talk about those unintended variables in your conclusions." Teachers also modeled the dynamic nature of science, which is less explored in NOS literature. Specifically, they allowed or encouraged students to re-select or invent dependent variables because previously selected variables were not feasible to measure or new variables worthy of investigation had emerged.

Concluding comments

We defined the learning environment in this study as authentic because: (1) students designed, conducted, and interpreted investigations with unknown outcomes, (2) students had epistemic autonomy in most aspects of their investigations, and (3) students worked with experts who provide assistance in meaning making. These characteristics reflect the conceptual, epistemological, and social aspects of science (Duschl 2008), which were also elements of the social semiotic framework used for analysis. As our results demonstrated, the conceptual, social, and epistemological aspects of science are largely intertwined. Many of the meaning making moves also had epistemological, conceptual, or social functions because they offered ways of knowing or of verifying knowledge. We believe this interconnectedness is a manifestation of the Vygotsky (1978) "social plane" on which individual meaning making is initiated.

Our results provide insight into the ways teachers and scientists can assist students' making meaning during scientific investigations. Their actions took place in a partnership where each assumed roles based on their positions and expertise. The semiotic framework helped us categorize and interpret their actions according to their functions. Scientists visited classrooms toward the end of the investigations to help students interpret their data and draw conclusions, and their actions served conceptual, social, and epistemological functions. Teachers assisted students throughout their investigations and their actions served all four functions.

In some instances, teachers' and scientists' actions were similar. For example, both teachers and scientists promoted a sense of scientific community by referring to others' research. Both helped students navigate the process of considering and reconsidering the methods of their investigations, especially at points when unanticipated outcomes arose. For example, students often selected or invented dependent variables at the outset of their investigations. As it became clear that not all variables were feasible to measure or analyze, both teachers and scientists acted to help students manage unanticipated outcomes. Ted accomplished this by advising his students to select or invent new variables. He implicitly highlighted the dynamic nature of scientific practice (Delaney 1994), which contrasts with a lock-step view of scientific methods often represented in science teaching. Susan addressed the role of serendipity in scientific research, an aspect of NOS not typically addressed in science classrooms.

Teachers and scientists also acted in distinct ways. As one might expect, teachers acted more frequently and in more varied ways than scientists to perform pedagogical functions of meaning making. Not only were teachers better prepared and positioned to act in the pedagogical domain, they had opportunities to interact with students throughout their

investigations. As such, teachers' interactions with students were not as limited by timing and context. Teachers and scientists also promoted a sense of scientific community in unique ways. Ted heavily emphasized the value of establishing a common understanding about the meaning of variables and making consistent measurements. In contrast, Sandy promoted a sense of scientific community by using scientific terminology over daily life terms in her dialogue with students. This explicit use of terminology offered a more sophisticated language for students to use in discussing their investigations. The scientists also addressed more diverse issues related to NOS than the teachers. Susan in particular pointed out both methodological and sociocultural aspects of NOS by referencing her own research experience. This type of real-world connection appeared to indicate to students that their research was valuable because it was connected with a larger research effort and had to potential to contribute to a larger body of knowledge.

For some students, learning science can be viewed as a “border crossing” during which they are required to move from the worldviews they experience in their family and out-of-school lives to the scientific worldview they experience in science class (Aikenhead 1996). Aikenhead and Jegede (1999) argue that the more similar the student's lifeworld is to the subculture of science, the more smooth their border crossings between the two worlds. Our results indicate that at least some students appropriated scientific terminology, using this terminology to make meaning of their results in their conversations with one another, their teachers, and their partner scientists. In these instances, scientists' use of scientific terminology appeared to be supporting students in crossing a border between classroom science and professional science. In instances where students struggled to appropriate scientific terminology, it may be that scientists' use of terminology in ways that were disconnected from students' current understandings was hindering the process of border crossing. In these instances, teachers play an essential role in translating technical ideas and terminology into a language that is understandable by students.

It is important to note that the roles and functions of scientists may differ in forms of inquiry other than controlled experimentation, which was studied here. In controlled experimentation, a great deal of time is spent selecting variables, establishing a common understanding of the meaning of variables, and making comparisons between variables. In a model building inquiry, however, students are more likely to go about making meaning by identifying and interpreting patterns among variables that explain the data. Further research should explore the roles of scientists in helping students make meaning in other inquiry settings. In addition, scientists' acts during the interpretation phase of students' investigations were the subject of this study. More research is needed to investigate scientists' roles and functions during other phases of inquiry.

These results are significant because they reveal the roles and functions of scientists during their interactions with pre-college students, which have been largely unexplored. Although the involvement of scientists in K-12 classrooms has been discussed in several documents (e.g., National Academy of Sciences 2010), these references are primarily “how-to” guides for scientists' work with K-12 students and teachers that are based on wisdom of practice (e.g., Tinker 1997). By considering the roles depicted in our study, scientists can better position themselves to contribute in unique ways directly related to their expertise. The organization of acts according to their semiotic functions also may be useful for increasing teachers' and scientists' metacognitive awareness of their roles in classroom-based partnerships (Jaipal 2010) and for making decisions regarding division of labor. Scientists can be tasked with highlighting aspects of NOS that are relevant to students' investigations, including how students' investigations fit into the work of the larger scientific community, while teachers can help ensure accessibility of knowledge to students.

Division of labor becomes more critical when opportunities to interact with students are limited. It is important to note that the scientists in this study interacted with students in person for only one 90-min class session. The brevity of this interaction could be seen as a limitation, as multiple in-person visits are likely to offer more frequent and diverse opportunities for interaction. Yet, this limitation represents a reality: scientists rarely are able to make repeated visits to the same classroom. In fact, the National Science Foundation Graduate STEM Fellows in K-12 Education, one of very few programs that support enduring, intensive involvement of scientists in K-12 classrooms in the United States, was cut from the 2012 federal budget. Thus, it is particularly important to understand the roles of scientists in classrooms where the duration of interactions are limited.

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Table 1

Semiotic functions of teachers' and scientists' acts during students' meaning making

Semiotic functions	Individual actions
<i>Conceptual functions</i>	
Increasing conceptual understanding	Explaining phenomena ^a
	Providing information ^a
	Interpreting results ^a
	Invoking new ideas ^a
<i>Social functions</i>	
Playing the role of knowledge authority	Confirming ^a
	Providing information ^a
	Explaining phenomena ^a
	Interpreting results ^a
	Invoking new ideas ^a
Promoting the idea of scientific community	Establishing a common understanding
	Referring to others' data and results ^a
	Explicit use of scientific terminology
<i>Pedagogical functions</i>	
Organizing ideas	Using visual organizers
	Summarizing student ideas
Increasing accessibility to knowledge	Providing daily life examples ^a
	Anthropomorphizing
	Providing analogies ^a
Checking students' knowledge	Checking students' knowledge
<i>Epistemological functions</i>	
Offering ways of knowing	Confirming ^a
	Providing daily life examples ^a
	Providing analogies ^a
	Referring to others' data and results ^a
Explaining aspects of nature of science	Explaining a nature of science aspect

^a Acts with dual functions are listed twice