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ABSTRACT

Teachers interested in fostering science learning through inquiry or projects must play a complex role in discourse with students. They must scaffold student activities in the classroom without taking away students' active roles. This paper provides a framework for a specific form of scaffolding open-ended science inquiry based on the notion of transformative communication. Case studies are presented from interpretive research in a project-based high school earth science class at two crucial and difficult junctures of projects--the formulation of researchable questions and the marshaling of evidence to support a conclusion through data analysis. In two cases, the teacher helps students transform information gathered from library research into seeds for their own original research seeking to confirm or falsify others' claims. In two other cases, the teacher helps students transform unsupported claims and poorly used graphical representations into analysis and representations that directly test their claims. It is concluded that the strategy of transformative communication proves to be a powerful means of supporting students. Contains 25 references. (Author/JRH)

Transformative Communication in Project Science Learning Discourse

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Abstract

Teachers interested in fostering science learning through inquiry or projects must play a complex role in discourse with students. They must scaffold student activities in the classroom without taking away students' active role, much like a coach. In this paper, we provide a framework for a specific form of scaffolding open-ended science inquiry, based on Pea's (1994) notion of transformative communication: (1) Students make a move in the research process with certain intentions, limited by their current knowledge; (2) The teacher does not expect the students' move, but understands how the move can have additional implications in the research process that the students may not have intended; (3) The teacher reinterprets the student move, and together students and teacher reach mutual insights about the students' research project through questions, suggestions, and/or reference to artifacts; and (4) The meaning of the original action is transformed, and learning takes place in the students' zone of proximal development. We provide specific case studies from interpretive research in a project-based high school earth science class, at two crucial and difficult junctures of projects—the formulation of researchable questions, and the marshaling of evidence to support a conclusion through data analysis. In two cases, the teacher helps students transform information gathered from library research into seeds for their own original research seeking to confirm or falsify others' claims. In two other cases, the teacher helps students transform unsupported claims and poorly used graphical representations into analysis and representations that directly test their claims. The strategy of transformative communication proves to be a powerful means of supporting students.

Introduction: A tree swaying between extremes

Educational reform efforts directed at fostering project-based learning have a tendency to substitute entirely teacher-directed pedagogy for entirely student-directed pedagogy (Rogoff, 1994). As Rogoff describes, *lecture-based* classrooms depend on transmission of knowledge from an active teacher to a passive learner. In contrast, *unguided discovery* depends on acquisition of knowledge by an active learner with the teacher remaining passive. However, the model of "*community of learners*" is based on the premise that "learning occurs as people participate in shared endeavors with others, with all playing active but asymmetrical roles." (p. 209). Teachers interested in fostering inquiry learning in their classes need to try to create a "community of learners" atmosphere. This implies that they must play a unique role of structuring and guiding student activities in the classroom without taking away the students' active role. Some researchers refer to this "middle ground" as "guided discovery" or "guided learning." The role of guide, however, is difficult to master. As Ann Brown says,

> Guided learning is easier to talk about than do. It takes clinical judgment to know when to intervene. Successful teachers must engage continually in on-line diagnosis of student understanding. They must be sensitive to overlapping zones of proximal development, where students are ripe for new learning. Guided discovery places a great deal of responsibility in the hands of teachers, who must model, foster, and guide the "discovery" process into forms of disciplined inquiry that would not be reached without expert guidance. (Brown, 1992, p. 169)

On top of the complexity of structuring and guiding students in project work, different students in a class *need* different levels and kinds of support, and they inevitably end up *getting* different levels and kinds of support. Matching the kind and level of support students *need* with what a teacher *gives* them is a difficult balance to maintain, though. Consequently, as one teacher put it, a teacher trying to support students can "feel sort of like a tree swaying between two extremes of providing students with structure and allowing them to do it all themselves." One way to conceptualize teachers' new role in such classrooms is by *scaffolding* student work (Collins, Brown, & Newman, 1989). Scaffolding can occur either by modeling, by structuring activity, or by coaching—supporting and guiding students' work along the way. In this paper, we describe and illustrate the use of one powerful form of coaching, transformative communication, in a high school project-based science class.

Methods and data sources

This research takes what Erickson (1986) calls an *interpretive* approach. Interpretive research refers to any form of participant observational research that is centrally concerned with the role of meaning in social life, enacted in local situations. It is part of a larger ethnography (Polman, in

progress) conducted over the past three years in Rory Wagner's[1] class. In the class students conduct Earth Science projects *of their own design.*

The first author has been a participant observer in Rory Wagner's classroom for three years—one and a half years acting as a technical assistant, and one and a half years conducting the formal study (1994-95 through winter 1995-96). Data collection techniques included written field notes and videotapes of classroom observation at each project phase, collection of artifacts created by the teacher and students, and formal and informal interviews of both the teacher and selected students. Formal interviews were recorded with audiotape and transcribed, while informal interviews were recorded with hand-written notes. For this study, the data is being used to uncover the ways transformative communication can scaffold students' accomplishment of projects.

Plesiosaurs: Transforming a quest for "the facts" into a research question

Three juniors who sit at the middle table of Rory Wagner's classroom during the first quarter of the year team up for their first project. Beth and Laura are both gregarious, and have participated frequently in class discussions during Rory's lectures. Cindy, on the other hand, is usually quiet and somewhat mousy.

After toying with a couple of different topics for their project, like volcanic islands, Cindy and Laura settle on dinosaurs, and then focus in specifically on the Plesiosaur. Beth is absent the day they make the choice, but is quickly just as enamored of the creature as the others, saying "isn't he cute?" when she sees a picture. They can be heard to repeat "pleee'-zee-oh-saur" slowly, relishing its sound, and they show anyone willing to look pictures of the dinosaur which lives in the sea. It has a long neck somewhat like a brontosaurus. In fact, it looks like the fabled Loch Ness monster, which some legends say is descended from the plesiosaur.

Following an activity structure for project-based science

During the first few weeks of projects, Rory has the students collect "background information" on their chosen topics. Beth, Laura, and Cindy initially have a great deal of trouble locating any specific details on the plesiosaur, but with Rory's help begin to learn how to use the Internet, which they can access from computers in their room, and they end up tracking down some useful resources on the World Wide Web and Usenet newsgroups. Along with some library books, they use the information to write up a Background Information report, which is one of Rory's "milestones" to completing a ten-week project. The complete series of milestones are as follows: (1) selection of group and topic, (2) Background Information write-up, (3) Research Question/Proposal, (4) Data Collection, (5) Data Analysis, (6) Complete research report modeled

[1]At his request, Rory Wagner's real name is used. All students' names are pseudonyms.

on the scientific research article genre, (7) Revision of research report, and (8) Presentation to the class.

This series of milestone assignments for students' project work embodies an "activity structure" (Doyle, 1979; Lemke, 1990; Mehan, 1978) for accomplishing projects. Jay Lemke points out that activities in the classroom are "structured" in the sense that they can be broken down into "functional elements [that] have specific relationships to one another, including restrictions on the order in which they can meaningfully occur" (1990, p. 199). In his observational studies of standard classroom "lessons," Hugh Mehan (1978) described how lesson activities are organized as sequences of events at various levels. The Initiation-Reply-Evaluation (I-R-E) sequences that Mehan showed are common in classroom lessons are an activity structure at the most basic level. Multiple I-R-E sequences are put together to form a "classroom lesson"—opening sequences to begin the class period, followed by topically related sets of sequences to cover instructional material, and closing sequences that end the class period. Extending this model, multiple class meetings can also have a structure or sequence: the typical five-day sequence at the high school described here is "Lecture-Lab-Lecture-Lab-exam." In Rory's class, however, he leads the students through an alternative activity structure with rich dependencies between the parts of the sequence. Some of the interdependence between parts of the activity, as well as the support Rory provides throughout the activity, is mediated by interim artifacts. The milestone artifacts are "shared, critiquable externalizations of student knowledge" (Blumenfeld, Soloway, Marx, Krajcik, Guzdial, & Palincsar, 1991; Guzdial, 1995, April) that become useful as occasions for feedback and transformative communication.

Negotiating a research proposal through transformative communication

During the following week, the Plesiosaur group has to come up with their focused research proposal. Rory conducts a whole class brainstorming session on formulating research questions around an example topic—wolves. After the class discussion, students begin working in their own groups generating questions about their topics. The next day, Beth and Cindy approach Rory, announcing they have a question. It is "Are accumulations of Plesiosaurs associated with areas of high marine productivity?" Rory sees a number of problems with the question. Although it suggests a "doable" empirical analysis—comparing the number of plesiosaur skeleton findings in locations to fossil records which indicate high marine productivity—the results would most likely be dubious because the fossil record is spotty. The problem is, the number and location of plesiosaur fossils found is so spotty that those records may not reliably indicate the relative numbers of plesiosaurs living at those locations in prehistoric ages. Fossils do not form as easily in some locations as others, regardless of how many animals lived in the locations, and fossils are

not as easily found in all locations. To avoid these pitfalls, Rory asks them to step back, saying "What drew you to plesiosaurs in the first place?"

Cindy talks about their long necks, and Beth about how they swim. That reminds Rory of a comment Beth had made while looking at library books two weeks earlier. She had announced, "This [book] says they flew through the water like sea turtles, and sea turtles swim very quickly ... This [book] says they didn't swim very quickly." Rory had only said "hmm" at the time and was interrupted by a question from another student. The group had not mentioned swimming speed in their background information report, but Rory had apparently filed it away in his mind. The following interaction takes place between Rory and Beth:

> **Rory:** Didn't you read a debate about whether they were fast or slow swimmers?
>
> **Beth:** Yeah. Some of them said they were fast and some said slow.
>
> **Rory:** Maybe you could do an analysis of swimming motion. Like how fast they go. You would need to know how animals move and how they swim.

Rory stresses that they need not follow his suggestion. Besides opportunity for learning through a greater level of student participation, Rory's policy of not forcing students to follow his recommendations is part of a general policy of leaving a large amount of responsibility with the students. If he *makes* students follow his recommendations, students are likely to claim he alone is responsible if their efforts do not turn out well, as a way of weaseling out of making improvements. But if students work together *with* him in earlier stages and have a strong voice in decision-making, they can establish *co-ownership*. With co-ownership of the project, students are more likely to be willing to work together with Rory to figure out productive alternatives if they encounter difficulties. Since Rory is "not driving the direction of anything, other than [laying] the framework," dialogue with the students becomes much more important, as we will see in the examples of tranformative communication.

Beth and the other members of the group like the idea, and decide to run with it. As Beth says, "it reminds me of the reanalysis of dinosaurs that they did, and whether they were slow or fast—Jurassic Park was more accurate than the old picture of lumbering dinosaurs."

Following this discussion where they decide to focus on the swimming motion of plesiosaurs, the group members go off to review the relevant sections in the library books they have gathered, and Beth returns a few days later saying incredulously, "Mr. Wagner! Do you know whether the plesiosaur moved by rowing its flippers or flapping them like wings?" One of her library books states that Plesiosaurs swam with a rowing motion, and another book states that they swam by underwater flight, flapping their flippers like wings straight up and down in the water. Neither book mentions a controversy. As Beth tells me later, "I thought he was like all-knowing. That he

like knew there was this controversy. But he didn't." Beth is also looking for Rory to provide *the answer*, the kind needed for what Rory calls a "traditional library research" project. She tells me she "had never done a project where there hasn't been really an answer, or someone who's already found the answer." Rory shows Beth that her question about the swimming method can be *the question* in *their* research project—*they* can assemble evidence and figure out which swimming motion they think it is.

The framework for transformative communication

Pea's (1994) notion of "transformative communication" helps explain how Rory is able to support Beth in accomplishing an activity with which she is unfamiliar. Transformative communication allows Rory and his students to accomplish learning and activity in Vygotsky's (1978) "zone of proximal development" (ZPD). Vygotsky's model of learning holds that learners accomplish activities with the help of more expert others in a social setting that the learners could not achieve on their own (on what Wertsch, 1991, terms the "intermental" plane between minds) . This social activity helps learners advance their own understanding, on what Wertsch terms the "intramental" plane within an individual's mind. Applying the model of the ZPD to teaching can prove elusive, however. How do teachers' know where students are? And what do students' contributions look like? For instance, when Rory is trying to help students formulate research questions for scientific inquiry, he has a dilemma:

> Finding the question, for me, is one of the hardest parts. I need to negotiate with them without taking over. I don't want to give them the question. I want them to generate a question. But how do I help them to do that? There's no clear path.

What is needed is some kind of interactive process which allows the student to be an active inquirer and the teacher to be an active guide. Transformative communication is one such process, and it provide some explanation of why some paths prove productive.

Pea contrasts his view of communication as *transformative* with views of communication as *transmission* and as *ritual*. As discussed in the Introduction, the dominant view of communication as transmission tends to encourage either an active role for the teacher and a passive role for the learner—i.e. lectures—or a passive role for the teacher and an active role for the learner—i.e., pure discovery learning. The view of communication as ritual tends to encourage active participation by all parties, but in activities with already shared meanings—the generativity needed for education is lacking. So Pea suggests the transformative view of communication. According to this view,

> the initiate in new ways of thinking and knowing in education and learning practices is transformed by the process of communication with the cultural messages of others, but so, too, is the other (whether teacher or peer) in what is learned about the unique voice and understanding of the initiate. Each participant potentially provides creative resources for transforming existing practice. (Pea, 1994, p. 288)

Transformative communication is achieved through mutual "appropriation" (Newman, 1984; Pea, 1992b) by participants in social interaction to create meanings that neither participant alone brought to the interaction. In a project-based science classroom like Rory's, designed to support students in carrying out their own original research, it involves transforming students' actions into more successful "moves" in the "language game" of science (Wittgenstein, 1967) ; put another way, this allows the students to participate in a new way in "talking science" (Lemke, 1990; Pea, 1992a). A general framework for transformative communication is:

(1) Students make a move in the research process with certain intentions, limited by their current knowledge.

(2) The teacher does not expect the students' move, but understands how the move can have additional implications in the research process that the students may not have intended.

(3) The teacher reinterprets the student move, and together students and teacher reach mutual insights about the students' research project through questions, suggestions, and/or reference to artifacts.

(4) The meaning of the original action is transformed, and learning takes place in the students' zone of proximal development, as the teachers' and re-appraisal (i.e., appropriation) of the students' move is taken up by the student.

The above interaction between Beth and Rory fits well into this framework: (1) Beth approached Rory looking for *the answer* to a fact-based question which she expected her "all-knowing" teacher to provide: did plesiosaurs swim by the "underwater flight" or rowing motion? If she could get the answer, she would include it in her report on plesiosaurs, which she may have been seeing still as a library research project like she had done in other classes, with established facts about a topic synthesized and described; (2) Rory did not know the fact Beth was looking for, nor did he even know there was a debate about plesiosaur swimming motion; but he did know that part of the game of science involves marshaling evidence to support one of several competing claims such as the ones in the books Beth had found; (3) Rory reinterprets Beth's move, saying "I don't know. Why don't you have that be your research question?" They talk about how she and the other group members could contribute new evidence to a scientific debate rather than just report others' findings; and (4) Beth's fact question has been transformed into a research question, as evidenced in her subsequent practice.

UFO Sightings: Transforming a citation into an opportunity for confirming research

Researchers on tutoring and project-based learning have pointed out that motivational benefits can be reaped when students are given *control* over decisions about what they do—as Rory gave Beth and her project partners—and when they are given the opportunity to work on problems and projects that *interest* them (Blumenfeld, *et al.*, 1991; Lepper, Woolverton, Mumme, & Gurtner, 1993). The problem, as Rory points out, with starting from students' interests and letting them

have a voice is that it is "awful hard" in many cases "to transform something you are really interested in to something you can do" as scientific research. Bruce, Sylvia and Cheryl's project shows how a project built on students' interests which are seemingly dubious from a scientific standpoint can be transformed into empirical research that is "doable." Through transformative communication, their project goes from being a project about "whether UFOs are alien space ships" to a project about confirming or falsifying natural explanations of UFO sightings.

Along with the other groups, the UFO Sightings group begin the project by collecting and synthesizing background research on the topic, before deciding on a specific research question. In their interim report of background research , they mention the so-called "Condon report" (Condon & Gillmor, 1968), the only official study of UFO sightings put out by the US government. Condon and his colleagues claimed UFO sightings could be explained by meteor showers, rocket launches, and other known phenomena.

Two days after he gets the Background Information reports, Rory says to the first author before class, "I should watch out for groups that need support instead of just waiting for it to become a problem. I think I'm trying to back off because I don't want to give them a topic and make it my project." Given the problematic nature of UFO projects in the past, Cheryl, Bruce and Sylvia are obvious candidates to provide with extra support, and Rory is intrigued with the group's description of the Condon report. In the meeting before class, he discusses the fact that Condon's analysis took an empirical approach based on supportable or refutable claims about alternate explanations for UFO sightings—essentially taking a scientific approach to a problem usually approached through mere hearsay. So during class that day, Rory initiates a discussion with the UFO Sightings group about potential research questions. The interaction with the UFO Sightings group proves pivotal in formulating a specific research question, and serves as another example of transformative communication.

Shortly after completing attendance and answering some procedural questions from various students about the research proposal assignment, Rory says, "OK, you guys," to Cheryl, Bruce, and Sylvia, and sits down with them. The following interaction takes place:

> **Rory:** OK, what do you want to do?
>
> **Bruce:** We want to show UFOs are alien space ships.
>
> **Rory:** [doubtfully] Any ideas on how?
>
> **Bruce:** I don't think there's any way to prove it unless they saw the alien in there and they waved at them. That's the only evidence there is.
>
> **Rory:** Right. That's the problem.
>
> **Cheryl:** I don't see why we can't write a report on it if people have written whole books on it. [Cheryl sees Rory's project at this point as essentially the same as an

> extensive report for an English class; such as the "Junior Theme" she had done the previous year. As time goes on, she begins to grasp the importance of using empirical data to support a claim.]
>
> **Rory:** [does not directly address Cheryl's confusion at this time] You know, Joe and I were talking about the analysis Condon did that you wrote about in your Background Information [report]. It was interesting because Condon claimed to have explained the sightings with known phenomena. [For your project] you could verify what somebody like Condon has done. That's another thing people do in science ..."

He gives them the example of the cold fusion debate a few years ago, and then points to how this could be applied in their project:

> ... these guys said they had created cold fusion in the lab. But when other people tried it, they couldn't duplicate what they said ... In science, once someone says they've proved something, others check it ...The idea [here] is to verify the government's explanations. Say they said it was a meteor shower. You could look at the date, where the meteor shower was, and when and where people saw the UFO. Does it match the same spot? If the sighting was here [points one direction] and the meteor shower there [points another direction] the government's explanation could be wrong.

The students decide to run with the idea. In this example, the students originally present the Condon Report as relevant to the history of the UFO debate, and thus something to be cited. Through their interaction, Rory and the students create a new meaning for the citation: the seeds of a study intended to provide independent confirmation or falsification. Thus, this sequence of interactions, starting with the submission of the report by the students and continuing with the discussion in class, can be seen as another instance of transformative communication. The students refer to some research in their Background Information report, intending it as an example of what is known and has been reported about their subject. Rory shows them they can treat the study as the seeds for the next phase of the activity structure: a research proposal to independently confirm or falsify the previous research.

We will not describe the rest of the UFO Sightings project in much detail. We will note, however, that this research formulation proves successful. For their final research report, the group chooses four UFO sightings from the 1960s described in the Condon report, and try to independently confirm or falsify the Condon report's explanation. The independent confirmation is based on printed data sources found in library searches: a nautical almanac (Casey, *et al.*, 1989) confirmed the position of a planet in the exact location where a UFO sighting was reported; NASA launch records (Stanford, 1990) confirmed that a scheduled re-entry of satellite Agena into the Earth's atmosphere occurred at the time an airplane crew reported a UFO over Mexico, and could have been seen in that location; a daily weather book (Thomas, *et al.*, 1979) confirmed that the local conditions matched those associated with mirages caused by refraction through warm, dry air, just

as the Condon report claimed. They could not confirm or deny the Condon report's assertion that a rocket launch explained a fourth sighting.

Rory Wagner feels that the "beginning of the project and the end of the project" are the most difficult for students. Specifically, at the early phase, students must formulate a research question and proposal, and at the later phase, they must use data analysis to reach an empirically supported conclusion. The Plesiosaur project and the UFO Sightings project provide examples of transformative communication during research question formulation. The Hurricanes and the Moons projects provide examples of transformative communication at the data analysis phase.

Hurricanes: Transforming an intuition into a coding scheme

Dave and TJ become interested in hurricanes because of the destruction they cause, and through conversations with Rory and a scientist mentor Rory assigns them settle on the research question "Is there a preferred pattern of hurricane movement in the Northern Hemisphere?"

Over the next two weeks, TJ and Dave work diligently to gather hurricane data off a Web site[2] they found linked from a page their mentor told them about. Rory reports early in week four that : "I have a gut feeling they don't know what they're looking for. They think it's a 5 minute process or they already have it." But Rory holds back, and lets them see for themselves what it takes to work with the images that show hurricane paths. It takes them a while to download images for a set of years, and they learn how to manipulate the images in graphics programs so that they can change the background color from black to white. They turn in a set of data just before the end of week five, and as they begin their data analysis, they realize they need to find a way to compare the paths on more than one image. TJ comes up with the idea of tracing hurricane paths by hand off the computer screen onto transparencies, which can be laid on top of one another. Now that they have gathered a body of data, Rory challenges them to go on to the next step of the project, figuring out "what the data says." The image of "talking with your data" comes from Rory's masters advisor. About his masters project, Rory said:

> [data analysis] is hard, though, for all of us. It reminds me of my masters advisor, who was a petrologist. We worked with igneous rocks, and the rocks became your data. He said, in his smiling face, "You have to talk to the rocks and the rocks will talk back to you." You have to poke it, sift it, organize it, and it'll talk back to you.

Through the processes of "poking, sifting, and organizing" all these images, and tracing their paths, the students have gotten a definite impression of what the data says about how hurricane paths tend to be shaped. In an interview outside of class, Dave notes that:

[2]http://thunder.atms.purdue.edu/hurricane.html

> We really are finding mainly that most of them are starting in a ... [they] start southeast of Florida and east of the Caribbean, and then kind of like they're really making a swoop up towards the United States, and then they die in the Atlantic. They make a little semicircle.

When he is asked to show on paper how the hurricanes tend to move, he draws the following:

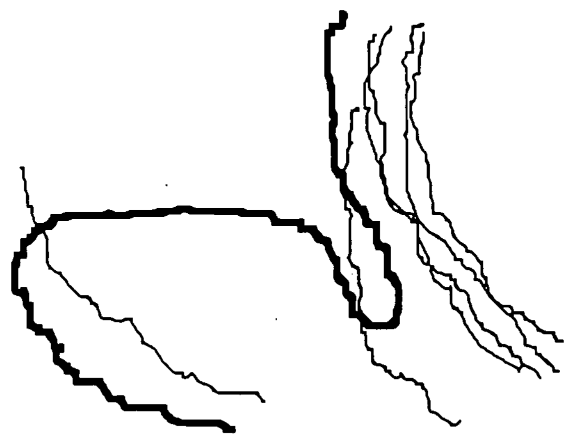

Figure 1: Dave's drawing of common hurricane paths

As he is drawing, he explains:

> **Dave:** ... They kind of like start here [southeast of Florida], and then they kinda swoop like that [along the East coast]. You know, and then some of them occasionally, you know [draws one going over Florida, and one into Texas/Louisiana].
> **Joe:** Right, those are the ones that blast over there.
> **Dave:** Some—that's like the general, you know
> **Joe:** Oh. And so they're always doing that [draws a C swooping from southeast to northwest to northeast]?
> **Dave:** Pretty much, yeah.
> **Joe:** And there's more of them over here [in Atlantic off coast]?
> **Dave:** Yeah, and generally some—you know, we've had a couple that have hit Texas, and some have gone up the coast of Mexico.

However, figuring out how to turn this general impression into an analysis of data proves difficult for Dave and TJ, much as it does for most of the rest of the class. They turn in an initial stab at an analysis of four random years and get some advice from Rory about choosing a larger sample of continuous years. After TJ and Dave download from the Web images for each year from 1985-1995, they trace them onto transparencies. In an effort to get an overview of all the data, they create a composite image showing all the hurricane paths from the eleven years. The students and Rory come to refer to this representation of all the paths together as a "spaghetti bowl"—there is so much data covering other data in the image that it is difficult to make sense of the whole thing. At this point in the project, TJ and Dave have to figure out how to put their burgeoning knowledge of hurricanes, and their impressions of hurricane paths into a coherent, written report, with

conclusions supported by data analysis. Like other students, TJ and Dave are having difficulty empirically supporting their conclusions.

With a day to go before their research report is due, Dave and TJ have a long conversation with Rory trying to solidify data analysis techniques. Rory asks them what the general pattern of hurricanes is, and TJ shows him the "C" shape Dave had described to me previously (see Figure 1 above). Rory suggests they think about where the hurricanes occurred—they could define the rectangular area that defined the boundaries of the hurricane paths. Borrowing inspiration from the constituent mineral analysis Rory had done as part of his masters in Geology, he also suggests the possibility of dividing the map up into cells of equal space on a grid. Then, they could count up frequencies of the hurricane paths through each cell of the grid, to see where the highest "hazard potentials" were for the 10-year period. As they continue to look over the "spaghetti bowl" of data, Rory notices that not all the hurricanes follow the "C"-shaped path Dave and TJ had described. Some are straighter than the standard C, and others appear erratic. He then suggests they could devise a categorization scheme for the shapes of paths. They could go back to each year, and put a morphological name on each hurricane, count up the frequencies of each shape, and calculate the percentages. He tells them he believes that analysis would be "valuable."

The conversation about data analysis was extremely productive, and Rory is excited about it. He observes after class, "there are a lot of things you could squeeze out of what they did instead of just the paths:" The only problem is, "the conversation [he] had with them ... should have taken place last week. It generated more ideas, but there [is] no more time." Not surprisingly, Dave and TJ's incorporation of these ideas is only cursory in the report they turn in on time the next day. Like most of the other reports, Rory finds Dave and TJ's report riddled with problems.

In his extensive commentaries written on the paper, Rory tries to be encouraging. On the front page, he begins with "Outstanding Effort! Don't quit now!" He tells them the "good things" are that they have "excellent data collection and manipulation," but the "bad things" include "Data Analysis extremely weak—but fixable!," and "can't support Conclusion from the Data Analysis." The group's statements in their Data Analysis are not supported well by the data. Rory's comments on this section of their paper begin: "You have lots of good data to analyze. But, you just packaged all the data into a pile, saying 'here it is,' and you made statements in this analysis section <u>without</u> referring to the data once. You <u>can't</u> do that." He points out specific examples. TJ and Dave had written, "We found that most of the recorded storms began in the Atlantic Ocean, east of the Caribbean and made a C-like shape towards the United States and finished back east of the northern United States." Rory comments:

> In <u>this</u> statement, you need to <u>show/prove</u> this is true. Which diagrams show this? Of the total # of storms over this 11 year period, exactly how many (and then, what

%) of the storms had this "C-shape" path. You need to show, in step-by-step fashion, how you came up with your Conclusions/Results. Back up what you say with your graphs.

After these comments, Rory proceeds to expand in writing on the various analysis strategies they had begun to flesh out together during class the previous week. First of all, how they could classify each storm in the time period as having one of a set of path shapes, such as the C-shape they mentioned. He points out that a complete analysis of "hurricane paths" also include issues of location and not just shape: where the storms begin and end, perhaps where they turn if they turn, what the boundaries of the "spaghetti bowl" of storms are, and how often each cell in a grid dividing the total area was hit by a storm. Rory ends by writing, "Bottom Line: Lots of ideas, late in the game. Which ones are 'doable' in the available time? You decide."

For their revised report, the boys carry out many of Rory's suggestions. They categorize each storm as having one of three path shapes, and give the number of storms within each category among the 83 storms over the period. They also produce a pie chart showing the percentages of each shape (see Figure 2).

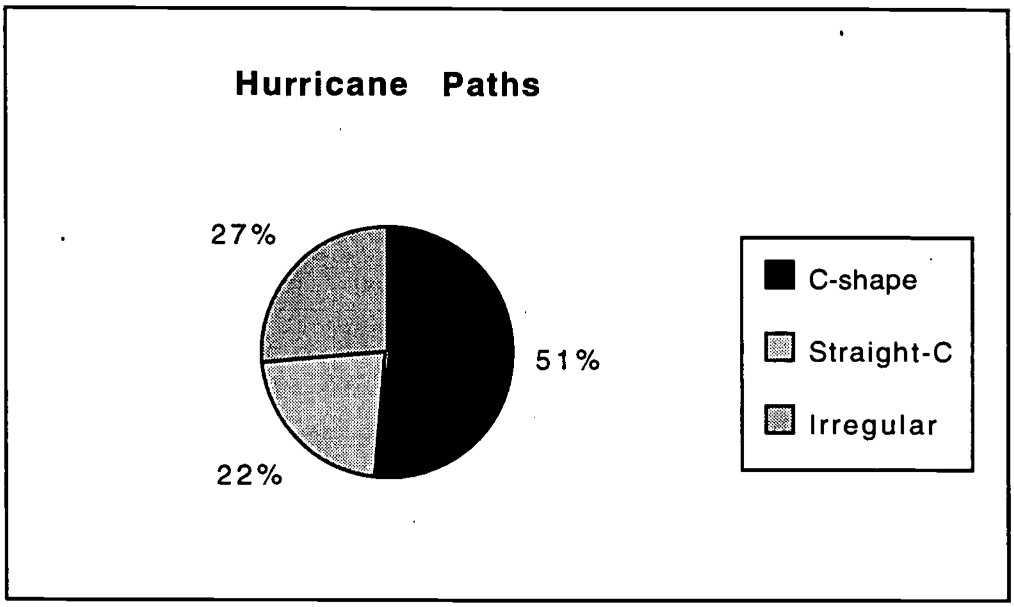

Figure 2: Pie chart of hurricane path shapes, from revised report

The hurricane group's revised report is a significant improvement over their first draft, with conclusions supported specifically by data analysis.

Moons: Transforming an unsupported claim into a graph of two variables

Rich and Steve are doing a project comparing and contrasting moons in our solar system. They have gathered data on various characteristics of moons, such as density, size, mass, and orbital

period, and meticulously organized it in tables and graphs—a separate graph for each variable. In numerous conversations and comments on interim milestones, Rory has been pushing them to think about questions their data could illuminate. For instance, "Why are they different from one another?" or "What are the connections [between variables]?" But the students are frustrated at finding patterns. As Steve put it:

> After we made all the graphs, we couldn't really analyze them, you know ... it was really hard to analyze them, 'cause there was really no pattern until [Rory] kind of helped us out a little bit.

The crucial exchange begins when Rory receives Rich and Steve's final research report. The students have included only graphs of single variables, and then listed each graph's interpretation separately. For instance, they include the following line graph of each moon's orbital time period:

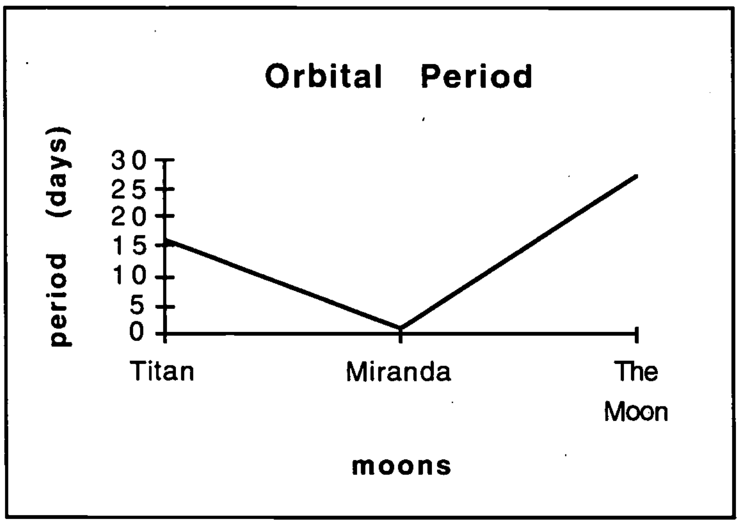

Figure 3: Orbital period of three moons from Final Draft

In the text, they write, "the graph [of orbital period] shows that Earth's moon has the longest orbital period, 27.32 days, while Miranda has the shortest orbital period, 1.4 days." Another one of the eight graphs shows the density of the moons:

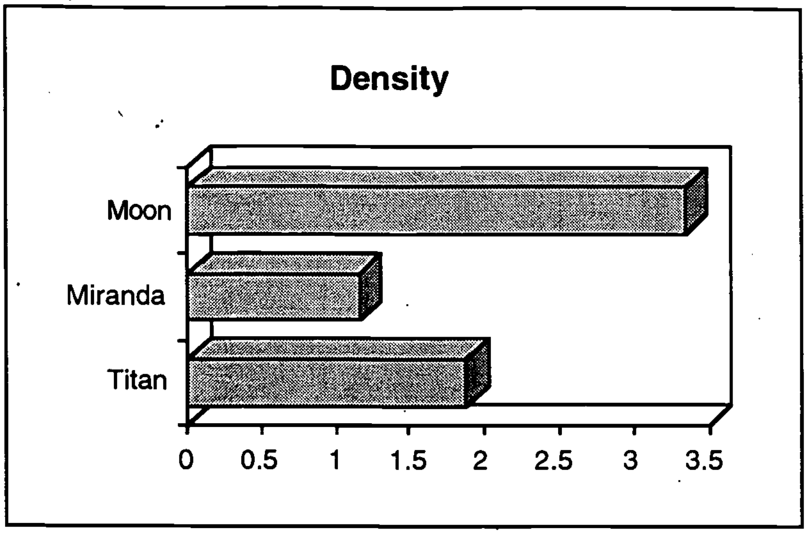

Figure 4: Density of three moons from Final Draft

Similar graphs in different styles are included for mass, surface temperature, and distance from planet. In the "Data Analysis" section of the paper, Steve and Rich do not mention relationships between variables, except in the statement that "Titan has a short orbital period in relation to its mass"—upon which they do not elaborate. But at the very end of the paper, buried in the Conclusion, something more like a testable claim appears. They have written, "We have come [to] the conclusion that both Titan and Earth's moon [have] a much greater mass and density than Miranda, and that this could be why both Titan and Earth's moon have longer orbiting time periods." Rory latches onto this claim about how mass and density could be related to the orbital period of the moons, and shows Rich and Steve how they can directly test it using their data, with graphs combining variables. He sketches a number of graphs like Figure 5:

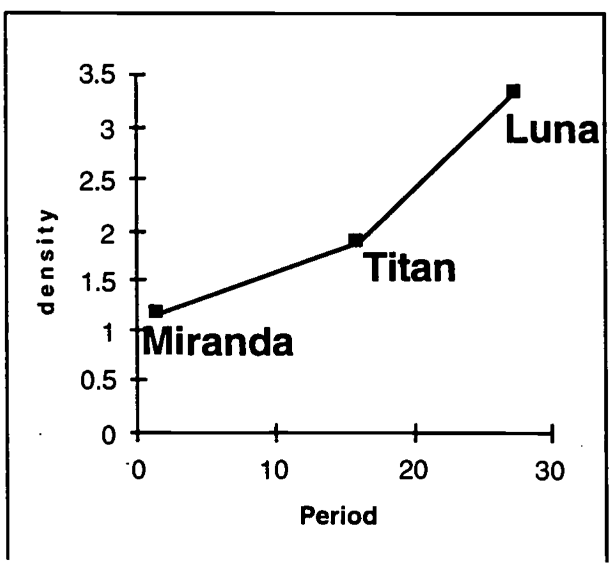

Figure 5: Rory's sketched graph ("Luna" is Earth's moon)

Once again, Rory sees how something that the students have done can be transformed to a more successful "move" in the "game" of science than they themselves were originally aware. In the course of working with the data, and looking at the graphs over a period of time, Rich and Steve have developed a sense that this relationship exists; that is why they put the comment in their conclusion. Recalling the image from Rory's masters advisor, Steve and Rich have "talked with" the data, and it has "talked back" to them. As we saw in the Hurricanes case, however, a clear analysis technique may be difficult to find even after the data "talks back to you." In this case Steve and Rich do not know how to construct a graph to directly test their claim. In fact, the graphs they have in their data analysis are not conducive to checking the relationships the students themselves mention in their conclusion—as shown in Figures 3 and 4, one graph is horizontal while the other vertical, and one is a bar graph while the other a line graph. Rory sketches graphs of one variable against the other to directly check the claim: it appears that in the students' data, a relationship between density and orbital period is supported, but not between mass and time period. Using similar methods, Rory suggests the students can create combination graphs for all the possible pairs of variables from their separate graphs. In this way, another apparent linear relationship is revealed, between the mass of a moon and its distance from the planet.

When Steve and Rich get the final version of the paper back, they are excited. As Steve put it,

> We finally saw, you know, what we were trying to find, with the patterns, by looking at those graphs. You know, we got all this information, now, and we finally saw what we wanted to see. With a little help from Mr. Wagner, giving some direction there. And that was ... a good thing. Seeing relationships.

Although there is no provision for revising their paper again, the students get a chance to use this insight in their presentation to the class the following week. Steve and Rich create graphs of their own using Rory's sketches as a model. In their presentation, they use the graphs as support for their claims, and a jumping off point to "come up with an explanation of why there [is] a pattern." The following is excerpted from their presentation:

> **Rich:** ... As I said, we were trying to find some patterns between certain things, and we did. We found [a relationship] between mass and distance. You can see here [he points to a graph like Figure 5, but showing mass on the y-axis and distance from planet on the x-axis, increasing on a nearly linear basis]. Um, we—that means that maybe—we think that if a moon has a greater mass that might affect its distance from the planet that it, you know, comes from.
> Also, we—between distance, uh, no, density and orbit time [he points to their drawn version of Figure 5]. Which also means it has a greater density, that that might affect its orbit time, meaning that it has a greater orbit time.
> **Steve:** You know, a larger density would contribute to a longer orbit time, and a smaller density would contribute to a faster orbit time.
> **Rich:** And those were the only categories that had patterns, or data that were, you know, similar.

With these statements about one factor "contributing to" or being "affected by" another, Rich and Steve have finally moved into the realm of making empirically warranted causal arguments, albeit tentative and somewhat awkwardly stated ones. As in the scientific community, they are making their claims with the aid of particular types of inscriptions—in this case, somewhat crude graphs. The graphs make their claim more compelling and understandable (Latour, 1988). In addition, they are able to see possible extensions of the work they've done: unprompted, Rich mentions a follow up project could "compare even more data, put them together, [and] see if there's a pattern." Steve adds that he would "go into more depth on the ... graphs that we made, and see if [the relationship they saw] relates to the other moons in the solar system."

Steve and Rich had a great deal to learn about analyzing data, but transformative communication helps them to begin making progress.

Mutual insights through conversation with one another and the situation

For effective teaching and learning, teachers simply telling the students what to do has important limitations. Rory wants to ensure that students participate in research design and the selection of analysis techniques so that they can learn about research design and analysis strategies. Traditional "cookbook" labs take such decisions out of the hands of students, but involving students can be time-consuming and difficult. The difficulty and pitfalls of student participation in the *whole* process of research has been recognized by a number of student-scientist collaborative efforts, but even though it is often messy from scientists' perspective to have students involved in the whole process, it is educationally significant (Pea, Gomez, Edelson, Fishman, Gordin & O'Neill, in press). Transformative communication can prove useful in maintaining this balance between student ownership and the teacher finding ways to guide students in potentially promising directions, since *both* parties make crucial contributions. As Rory described it,

> sometimes [students] come up with things that are really creative that I would have never thought about, which then lead me to think of other things that might be doable. And sometimes—[and] this gets in to the negotiating thing—sometimes they get real close to something, or have a neat idea, but it's not doable, so then, how do you turn that into something that is doable? Sometimes they do it, sometimes I can do it.

And in some cases like those detailed above, the students and teacher can truly do it together. In the interactions described, Rory helps the students transform the moves they make in the research process with limited understanding into more sophisticated moves that neither he nor the students would have originally predicted, thus leading to *mutual insights*. The interactions can take place over an extended period of time, in real-time or written discussions, but the important things is that *both* teacher and student participation contributes. To borrow a phrase from Donald Schön (1982),

the process of transformative communication enables both Rory and his students to "engage in a conversation with the situation which they are shaping" (Schön, 1982, p. 103), but in this case it also allows them to engage in a conversation with each other. Whereas Schön was talking about reflective practitioners of design, such as architects, working alone, the process is remarkably analogous in these social interaction between teacher and student. Architects are "likely to find new and unexpected meanings in the changes they produce [in their drawings] and to redirect their moves in response to such discoveries" (p. 103), but Rory and his students are likely to find new and unexpected meanings in the changes they produce *in one another's interpretations* and *the situation*. As Rory tries to tell the students, they *do* know important and useful things about their topic and data as they get further into their topic, but he often needs to help them *see* how what they know can be used to accomplish scientific inquiry. Rory and the students "come to appreciate and then to develop the implications of a whole new idea" (p. 95).

In these cases, the "activity structure" that Rory has designed for conducting projects helps him to support students through transformative communication. The activity structure sets up the students' desire to formulate a researchable question, or an analysis strategy that will help them to answer their question, and Rory makes suggestions which help students see how the work they have done and knowledge they have gained can help them get to the next stage in the activity structure[3]. As Rory has found in his project-based teaching, students learn on a need to know basis—"they won't care [about data analysis strategies] until they have to do it." But when they do have to do it, they can more readily recognize how the strategies Rory is trying to teach them are helpful.

Learning in the ZPD

Although the focus of our current research is not on individual learning, we would like to point out some evidence of how transformative communication such as that demonstrated in the interaction between Rory and Beth can result in individual learning. Again, the Vygotskian notion of the ZPD suggests that the activity which Beth and Rory accomplished on the intermental or social plane could result in learning on the intramental or individual cognitive plane. In the plesiosaur project, Rory helped Beth see that claims about the phenomenon of plesiosaur swimming motion need not be accepted as simple "fact" or "fiction," and together they figured out some strategies to attempt to independently confirm or falsify claims about the claims by assembling independent data. In her next project, Beth chooses underground nuclear testing as her topic, and soon encounters claims from environmental organizations and the French government that such testing causes geologic

[3]The interdependence involved in transformative communication described here recalls Pea's (1992b) case that intelligence is distributed. In this situation, to achieve a higher level of intellectual activity, Rory, his students, and the activity structure work together as a system to attain its results.

damage. After doing further investigations, she suggests, with no prompting from Rory, that these organizations are making catastrophic claims without data to support their conclusions. She even goes so far as exploring the idea of making a Web page to publicize her position.

Conclusion

Project-based science teaching and learning involve complex role changes for teachers and students. Too often, the complex work teachers perform as facilitators and guides for project-based student work is left mysterious. In this paper, we provided a framework for transformative communication, one productive strategy teachers can use in the role of facilitator. We also elaborated concrete cases in which this strategy has been used successfully to help students accomplish projects more sophisticated than they could originally conceive.

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