Meaningful Collaboration in Secondary Mathematics and Science

Teacher Professional Learning Communities

Michael Oehrtman
Arizona State University
oehrtman@asu.edu

Marilyn Carlson
Arizona State University
marilyn.carlson@asu.edu

Judy Sutor
Arizona State University
judy.sutor@asu.edu

Linda Agoune
Arizona State University
linda.agoune@asu.edu

Carla Stroud
Arizona State University
carla.stroud@gmail.com

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Introduction

Based on an analysis of video data from the Third International Mathematics and Science Study (TIMSS), Stigler and Hiebert (1999) argue that teaching reform efforts in the United States are too often limited to short-term success due to embedded and pervasive cultural practices too great to overcome through standard professional development activities. They argue that real change requires career-long learning and focus on student thinking and classroom practices. Efforts to achieve these goals are exemplified by the model of Japanese lesson study in which teachers collaborate to develop, evaluate, refine, and disseminate new instructional ideas (Yoshida, 1999; Ma, 1999; Stigler & Hiebert 1999; Shimizu, 2002).

Project Pathways is an ongoing Math and Science Partnership at Arizona State University supported by the National Science Foundation to implement and research teacher professional development in six large urban school districts in Arizona. One component of Project Pathways has been school-based Professional Learning Communities (PLCs) for interdisciplinary groups of secondary mathematics and science teachers. PLC sessions engage teachers in conceptual conversations about knowing and learning central ideas in secondary mathematics and science, discussion and assessment of student thinking, development of inquiry-based conceptually-focused lessons, and reflection on the effectiveness of their instruction.

We report results from a five-year study of the implementation and support of Pathways PLCs promotion of *meaningful collaboration* among the participants. By *meaningful*, we emphasize the need for long-term, scientific engagement of issues of teaching and learning, such as that promoted in Japanese lesson study. We emphasize *collaboration* as an essential goal for these communities is to open teachers' classroom doors to the "critical colleagueship" of their peers (Lord, 1994; Garmston & Wellman, 1999). This research report summarizes attributes that differentiated high from lower performing PLCs.

Discipline-Specific Frameworks

The design of all aspects of Project Pathways and initial data analysis was informed by existing frameworks specific to the disciplines of engaging in mathematical problem-solving, scientific inquiry, and engineering design.

Carlson and Bloom (2005) developed a *multidimensional mathematical problem-solving framework* through empirical studies of the cognitive and meta-cognitive processes of research mathematicians and by drawing on a history of analysis of problem solving extending from Polya's (1957) book <u>How to Solve It</u> to Schoenfeld's (1985, 1989, 1992) cognitive studies and frameworks. Carlson and Bloom's framework characterized problem solving along dimensions corresponding to an individual's behaviors and attributes. The mathematicians' problem-solving behaviors were cyclical in nature, consisting of four primary phases (see Figure 1). They first oriented themselves to the nature, elements, and structure of the problem. They then conjectured solution paths, rapidly evaluating the potential effectiveness and requirements of each before making a decision on how to proceed. Once they began executing their chosen plan, they monitored their progress, reverting back to the planning phase if things were not going well or if new information was discovered. Finally, the mathematicians also monitored their work for sensible and useful progress then ultimately for whether a viable solution had been achieved. Based on their assessment of their outcomes, they would communicate their solution, or cycle back to revisit previous work, or cycle forward to develop new ideas.

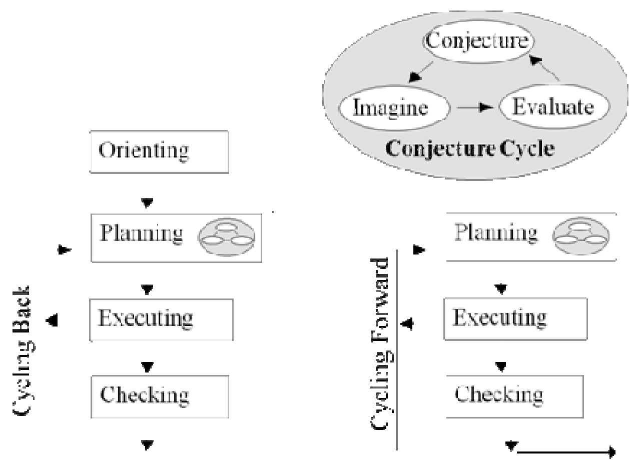


Figure 1. Individual behaviors in Carlson and Bloom's problem-solving framework.

The second dimension of Carlson and Bloom's framework characterized attributes of the individual mathematicians crucial to their success during each of the problem-solving phases. These attributes included available resources such as knowledge, experience and heuristics and an ability to modify them. It also included affective qualities such as curiosity, intimacy, frustration, defense mechanisms, ethical concerns related to their reasoning and adherence to intellectual integrity. Finally, this dimension characterized metacognitive skills such as motivation and attention to efficiency and aesthetics (Carlson, 1999; Carlson & Bloom, 2005).

A second framework guiding the design of the Pathways intervention and initial coding of data was *the hypothetico-deductive reasoning cycle* (Wallas, 1926; Koestler, 1989; Lawson, 2001). In this framework, human discovery, problem solving and invention is initiated by an encounter with a problem or observation that contradicts one's current expectations about how the world should work (see Figure 2). The individual generates multiple hypotheses through analogical reasoning or abduction, many of which may lead to a dead end while others are selected for further investigation. This phase of reasoning is preparation for creative thought, and the individual will often set the problem aside, where it may incubate subconsciously. Later, possibly while engaged in seemingly unrelated pursuits, they may have a flash of insight about the original problem. Lawson (2001) characterizes this as the formation of an analogy link between the original plane of thinking and a new plane containing a target solution. Once this illumination or flash of insight occurs, a hypothetico-deductive verification process may begin. These steps are iterated until an alternative is generated, tested, and supported on one or more occasions and its competitors have been tested and rejected.

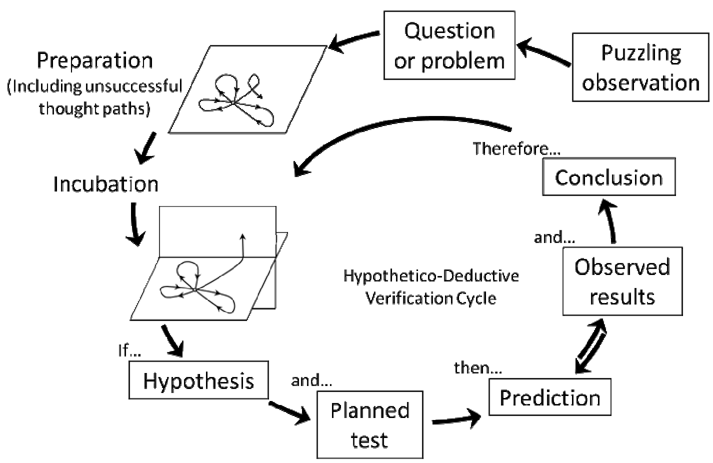


Figure 2. Lawson's characterization of the scientific inquiry cycle.

Descriptions of *the engineering design process* have been presented in many different configurations (Atman et al. 1998, 1999, 2001, 2003; Fogler and LeBlanc, 1995; Voland, 1999) but all divide the design process into phases strikingly similar to the previous two frameworks (see Figure 3). Atman et al. (2003) noted that a key distinction between expert and novice engineers is that experts often rapidly cycle between multiple phases, even when they are ostensibly engaged in one single phase as viewed in terms of a project plan. Most representations of the design process are also explicitly cyclical. For example, Voland's representation arranges the steps on a circular figure and Atman's incorporates cycling back to earlier steps at every step of the process. The result of any step might be a decision to revisit an earlier step, for example, results of feasibility analysis might illustrate the necessity of redefining the problem.

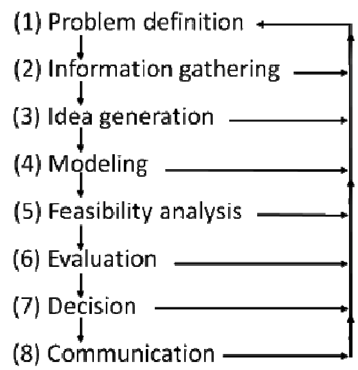


Figure 3. Atman's characterization of the engineering design cycle.

Methods

Project Pathways PLCs have school-based facilitators who are responsible for managing the discourse during the PLC sessions. The facilitators received 18 hours of summer training and attended monthly 3-hour training meetings during the semester. Facilitators were provided general agendas developed by project personnel designed to assist them in promoting meaningful discourse among members of the PLC, although they were encouraged to deviate from the agenda as needed to pursue particular needs of the PLC. Project personnel reviewed video tape of the PLC sessions and discussed facilitation strategies during 30-minute weekly meetings with the facilitators at their school. All teachers also attended masters-level courses for three hours each week focusing on integrating mathematics and science content related to the PLC activities.

We collected and reviewed video data from every course and PLC session and selected over 100 hours of video from the courses and over 100 hours of video from the PLCs for indepth analysis. Two research teams engaged in multiple rounds of open, axial, and selective coding (Strauss and Corbin, 1990) relative to issues defined by the three discipline-specific frameworks. At semiweekly research team meetings we compared and discussed coding and constructed timelines indicating the flow of coded activity through each episode. We added major events to these timelines where the teachers made breakthroughs, gave up on their work, argued, etc, then reviewed the timelines for patterns. We generated initial hypotheses about these patterns and interviewed teachers from the project for additional information and feedback on our characterizations of their work. We developed fixed coding categories, criteria and numerical scales and engaged teachers, personnel, and researchers from the project in coding and scoring selected video. Through this process, we identified aspects of the coding scheme that did not adequately apply to the data and on confusing categorization or criteria. Based on this data, we revised the codes and criteria to produce the following framework outlining the most crucial factors in a PLC operating productively and the observed relationships among these categories.

Our analysis resulted in the emergence of three central categories of *process behaviors* generalizing the discipline-specific frameworks for STEM inquiry and three categories of *dispositional behaviors* related to participants' approach to their discourse. The remainder of this paper will describe these categories and their relevance to creating and supporting effective professional learning communities. While it is beyond the scope of this paper, we note that our analysis also produced a central theoretical construct of decentering, following facilitator moves to manage discourse in their PLC, and four categories of teacher beliefs that influenced their ability or willingness to change their own teaching practices.

Results

We illustrate our findings by presenting an analysis of one episode of a PLC engaged in an integrated mathematics and physics activity designed to foster meaningful use of graphical, numerical, and algebraic representations in context. This analysis will illustrate the central categories of process and dispositional behaviors that emerged from the study. We then characterize a generalized framework for teachers' inquiry into the content of their discipline, student thinking and learning, and their classroom practices. Finally, we illustrate how this generalized framework was used in subsequent analyses by contrasting the development of two PLCs in their first semester of meetings.

The following depicts one teacher's struggles to make sense of graphical data, and how comparisons with what he understood about the context enabled him to identify and resolve a problem with the data that his group had collected. In this activity, the group positioned a motion sensor to collect distance vs. time data for a cart as it rolled down an inclined ramp. Figure 5 illustrates the set-up that they were using and a graph of the data that they collected.

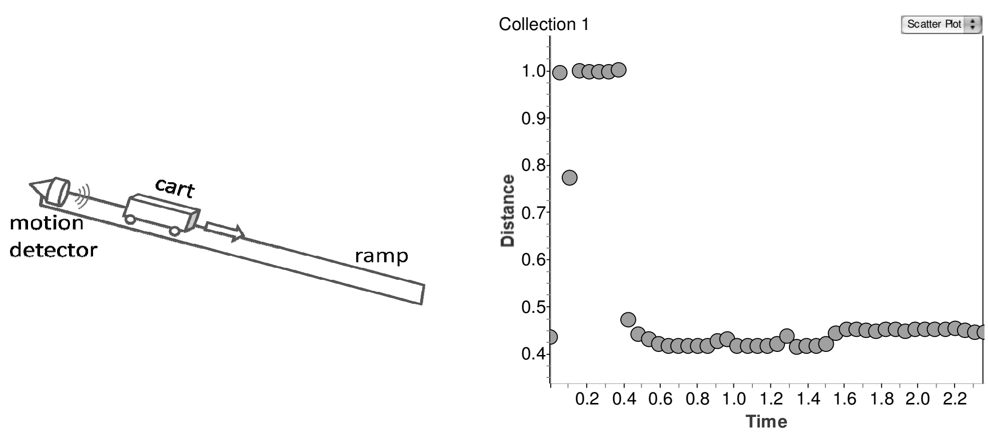


Figure 5. Configuration of the cart-ramp experiment and the data collected.

After the 5 teachers had collected this data, a biology teacher who regularly expressed doubts about his mathematical knowledge began raising concerns.

Dave: (*looking at the data plot*) But that doesn't make sense, 'cause that's not a fraction of a second that that took place. It took more than a second to go from there to there (*motions to the top and bottom of the ramp*).

Sharon: (*Rolls the cart up the ramp and back down, and counts*) 1, 2, 3.

Dave: Right, (*pointing at the data on the computer screen*) but this is showing that it went from .4 to .8, .4 of a second.

Sharon: It's about .8 of a second when it hits down here.

Notice that Sharon was not responding to Dave's claim, rather she interpreted his statement to be that the cart took .8 seconds to travel down the ramp. She ignored her own assessment that it took 2 or 3 seconds for the cart to roll down the ramp in order to assert that there was no problem. Jim and Therese responded by saying that they had zoomed in and cut off some of the data, explaining why the interval is so short, also dismissing Dave's concern without directly addressing it. Therese then suggested that they run the experiment again, and they timed it with a stopwatch in addition to collecting the data electronically.

Jim: About 1 second. (*Sharon Nods*)

Dave: More or less than a second?

Sharon: It's gonna be a little less than a second?

Jim: It's about 1.35

Therese: (*Looking at the new data*) I don't know if it is because of the noise in the room, but it goes up and down like this (*waves her hand up and down*).

Sharon: It's because it doesn't go off of the start right away.

Sharon continued to argue for the validity of the data, adjusting her description of events to match a desired outcome. Jim and Therese were willing to re-collect the data, but their comments suggest that they still did not understand Dave's arguments. Dave was trying to establish that the cart took more than 0.4 seconds to travel down the ramp, but even when they verify that it took 1.35 second, the others were still not convinced that there was a problem with the original data that they collected. However, Sharon, Jim and Therese were not satisfied with the new data that they collected either (e.g., Therese said that it looked like noise), so they spent time playing with the physical set-up of the ramp, hoping that they could find a way to "get a few more data points." Meanwhile, Dave continued to look at the original data and reiterated his argument about the timing, and Sharon, Therese and Jim repeated responses that did not address Dave's concerns. Dave continued trying to understand their responses, carefully comparing the data to each point they raised. Eventually, Dave raised a different argument:

Dave: We should be getting accel… a curved line all the way until it gets here.

Sharon: It will curve at such a minute rate because there are so few data points, we're not gonna be able to see the curve. It's kind of like standing on the face of the earth; you don't see the curve because it is so great. You don't see it here because we have so few points. If we had more points you'd be able to see more of the curve.

Dave: But the curve is here (*pointing to the data*).

Sharon: that's a bounce though (*walks away, seeming frustrated*).

Dave: See, when you had it parked and the thing was going like this… flat (*pointing at the data*), and then we let go. Those first few moments it's going the very slowest it's ever going to go. It gains speed all the way down. Our curve doesn't show that. It doesn't show it. It shows it slowing down.

Therese: Our curve shows it's slowing down?

Dave: Yeah – a curve that goes like this (*motions with his hand*).

Sharon: It's showing the position coming closer; time is accelerating

Sharon seemed to be confusing the shape of the graph with the actual motion of the cart traveling down the ramp. Dave did seem to have caught Therese's attention when he said that the curve suggested the cart was slowing down as it moved down the track. As he continued to compare the context to their interpretation of the graphical representation of the data, he became increasingly convinced that the data was incorrect. As he highlighted inconsistencies, both Therese and Jim began to appreciate these problems, leaving only Sharon to defend the data. The instructor noticed that the group was having a conflict and walked over, and Dave raised a third inconsistency in the data.

Dave: The meter was up there and [the cart] was rolling away from it. The distance should have been getting bigger. It wasn't getting bigger on this (*points to the graph*). As it rolls away, that distance number should be getting bigger… and the speed should be picking up.

Sharon: But change in position is getting smaller, that's why it gets closer and closer together near the bottom.

Dave: But the meter was up there and the cart was rolling away.

Sharon: It's moving away so there is a big jump at first, and it gets slower and slower… changes get slower and slower.

Sharon's responses to Dave were all based on the data that she without consideration of the context. As a result, Sharon seemed to be confusing *position* with *change in position*.

Dave: No, no. It gets faster and faster as it goes down.

Instructor: And the graph should be going up.

Dave: Right – and it's not. It's dropping down. And that's not what it should be doing.

Instructor: (*Walking around the table to look at the data on the computer screen.*) Oh – this is what's happening. As soon as the cart moves, it's left the view, so [the sensor] isn't picking it up at all. So what we need to do is go back to the data collection.

The instructor helped the group re-collect the data, standing a card on top of the cart and explaining that this provided a bigger target. The whole group then evaluated the data on the computer screen, and agreed that it matched their experience of the context.

This episode provides an example of how a teachers' reflection about the situation helped resolve a problematic issue. Dave's inferences among the data and the context generated insights that the others did not see. He possessed the necessary conceptual resources to evaluate whether the graph accurately reflected the situation and noticed at least 3 discrepancies: 1) the graph indicated it only took the cart 0.4 seconds to roll down the ramp, 2) the graph indicated the cart was slowing down, and 3) the graph indicated that the cart was getting closer to the sensor.

In addition to Dave's attempts to make sense of the graph, he also took the issue of communication with his group members as problematic. Initially, he appeared to feel that he had made an indisputable point when the stopwatch verified that the cart took 1.35 seconds to roll down the ramp. But the other group members did not see any problem with this. In response, he became quiet and spent more time pondering the data. He asked for clarification, but the arguments made by the other group members did not sufficiently address his concerns. His evaluation of their responses indicated that he had not been successful convincing the others, so he began to expand his argument. He eventually succeeded in getting the attention of the other teachers, and had convinced all but Sharon by the time that the instructor became involved.

It is impossible to say what the other teachers were taking as problematic in the early part of this episode. They spent a significant amount of time adjusting the ramp. Sharon in particular made a number of comments about needing more data points, and used the issue of their lack of data points in arguments with Dave. They all responded to Dave concerns, but they did not seem to have evaluated whether their explanations appropriately resolved them. In the end, they all made sense of the final graph, indicating that they had the necessary content knowledge to understand what Dave was saying. The obstacle to applying these resources in a productive way was that they did not engage as critically and reflectively Dave.

Generalization of the Discipline-Specific Frameworks

We found that generalizing the three discipline-specific frameworks helped us identify multiple instances of similar behaviors and account for interactions of ideas across the STEM disciplines. We subsequently developed a scheme for coding and taking theoretical notes framing all research questions as part of the larger question: *What is the nature of the group's* ***interactions*** *and how do they advance* **inquiry** *into important* ***structures***? The three discipline-specific frameworks may differ in their details, but the key features of any such inquiry are that it is active, testable, and productive. We drew on John Dewey's theoretical constructs of *inquiry* and *emergence* for crucial aspects of cognitive tool use (Dewey, 1910; Hickman, 1990). Dewey defined reflective thought as "active, persistent, and careful consideration of any belief or supposed form of knowledge in the light of the grounds that support it, and the further conclusions to which it tends" (Dewey, 1910 p.6).

Dewey distinguished reflective inquiry from the bulk of *non-reflective* or *routine* human experience in which nothing has become problematic and one may operate on commonplace understandings and expectations (Hickman, 1990). When an aspect of a situation is taken as problematic, however, one's engagement may become inquirential, reflecting a process illustrated in Figure 4. Inquiry is active in the sense that one purposefully chooses specific tools (including ideas or language) to apply to the problem. These tools are then used to probe the situation, thus changing it. Inquiry is testable in the sense that the system provides feedback about the tool, idea, or language initiating reflection on the tool itself and its interaction in the system. Inquiry becomes productive in this dialectic between the tool use and the problematic issue, through which new ways of perceiving and understanding emerge.

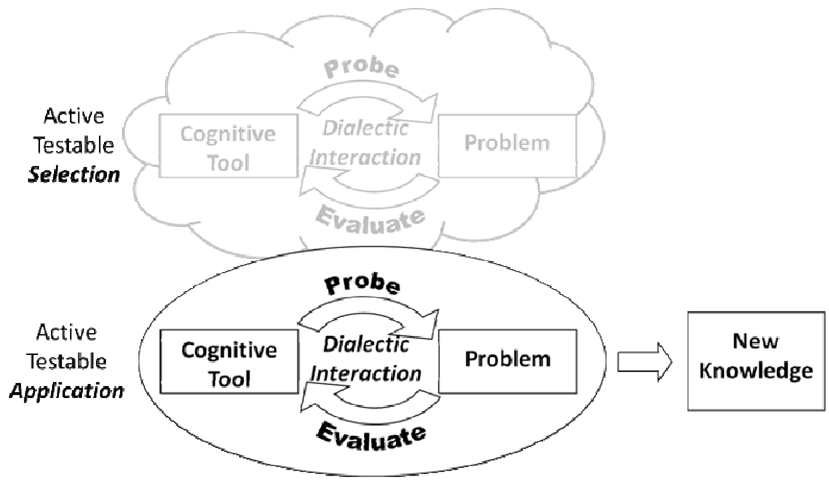


Figure 4. Dewey's characterization of inquirential engagement.

Productive learning communities

A central goal of Project Pathways was to engage teachers in inquiry into their own content understanding, student reasoning and learning, their teaching practice and issues of their communication with one another. In the preceding example, we saw Dave inquire into content issues. A teacher might also inquire about what it means to understand a particular idea, which is critical when developing lessons. Inquiring into the understanding of others involves imagining how that person must be thinking to say what they are saying and has the potential to strengthen teachers' inquiry into student reasoning. Fostering a practice of inquiry captured two central goals of Project Pathways: developing expert mathematical and scientific behaviors and providing a model for inquiry-based instruction.

Process Behaviors. Process behaviors focus on the interactions within a PLC aimed at achieving a specific goal. The three central categories of observable behaviors that emerged from our analysis are: productive engagement, conceptual resources, and persistence and reflection.

Productive engagement refers to a group's initial entry into the inquiry process: taking something as problematic and engaging reflectively rather than routinely. In the episode described above, Dave provided a good example of this kind of engagement. Sharon, Jim and Therese appeared to be more routinely engaged as they were working through the assignment, but they were not involved in the kind of "careful consideration of … (some) form of knowledge in light of the grounds that support it" which Dewey defined as reflective thought. Applying this framework to study a group of teachers, we sought evidence that the members were exploring common problematic issues and that all members were encouraged to participate. An example of unproductive group engagement would be evidence that the group is routinely working through the agenda for the session, that the group is not focused on a common issue, and that some group members are excluded from participating.

The category of *conceptual resources* captures both the active selection and application of tools. It is typically impossible to observe a group's selection of tools, since this is a process that may occur largely without discussion. But it is often possible to observe group members applying the tools that they have chosen the problem. For example we saw Dave making various comparisons between the graphical data and his experience of the cart rolling down the ramp and considering additional arguments to help convince his group that the data did not make sense. We sought evidence that groups were intentional in their selection of conceptual tools and applied them appropriately. Although we did not anticipate that group members will have the content knowledge to resolve every problem that they encounter, we also sought evidence that groups sought outside resources when they encounter a gap in their understanding. Less productive groups might be seen applying resources indiscriminately or inappropriately such as offering irrelevant or incorrect arguments.

In the category of *persistence and reflection* we sought evidence that a group evaluated the effectiveness of the tools that they applied. The previous episode illustrates Dave's evaluation of whether his observations about discrepancies between the graphical data and the situation itself made sense and whether his arguments were understood and accepted by his group members. On the other hand, Sharon, Jim and Therese offered arguments that were not relevant to the questions Dave raised. They were not evaluating whether the tools that they had chosen to apply to the problem were effective. In general, we expect a productive group to reflect on the effectiveness of their solutions and to persist until a problem is resolved. A nonproductive group might give up easily when they are not sure how to solve a problem, offer suggestions that are not appropriate to the problem at hand and not evaluate their solutions.

Dispositional Behaviors. Dispositional behaviors refer to attributes of a group that we have found to have a strong influence on their productivity. The first dispositional behavior category that emerged from our analysis focuses on whether a group *seeks a conceptual rather than a procedural understanding*. Thompson, Philipp, Thompson, & Boyd (1994) characterized a conceptual teacher as one whose actions are driven by: an image of a system of ideas and ways of thinking that she wants the students to develop, an image of how these ideas can develop, ideas about materials and activities that can orient students to these desired ways of thinking, and an expectation that students will be intellectually engaged with the materials and activities. A conceptually-oriented teacher will focus on aspects of a situation that give meaning to numerical values, whereas a teacher with a calculational orientation has a tendency to speak exclusively in the language of numerical operations, and has a tendency to disregard the context in which calculations might occur. This orientation aligns closely with the conceptual approach that we find in the most productive groups.

The second dispositional behavior category is *intellectual integrity*. It was important that the teachers were honest about what they did and did not know and that they were willing to challenge each other. In the most productive groups, teachers justified their comments and expected others to do the same. In their study of high school English and History teachers coming together to develop an integrated curriculum, Grossman, Wineberg, & Woolworth (2001) found that early on, teachers displayed what they called "pseudo-community" in which teachers are overly polite and agreeable, rather than being honest about what they did not understand, or challenging others when they disagreed. We found that this willingness to be honest, and a willingness to push for understanding; to challenge and be challenged, is crucial for productive discourse. Ma's (1999) study of Chinese teachers' mathematical knowledge illustrates the importance of providing rationale for claims. One of the primary differences between US teachers and Chinese teachers that she highlighted was that while US teachers typically described the algorithm that they used when solving problems, the Chinese teachers solved the problem and discussed their rationale. This practice of justifying comments or problem solutions contributed to productive discourse in the group sessions.

The third category of dispositional behaviors in a productive group is that they *seek a coherent and connected understanding* of material. Ma's work also highlights the importance of coherence in teachers' mathematical understanding. Ma described Chinese teachers' coherent and connected understanding of fundamental mathematics as a crucial factor in the quality of the teachers. Within a PLC session, seeking a coherent and connected understanding is exemplified by looking at multiple representations, or multiple ways of arriving at a solution. In a productive group, we would expect the members to establish connections among ideas and to generalize conclusions to other settings. An unproductive group might treat ideas as unrelated, or members might not be open to solutions other than their own.

Evolution of Inquiry in a Nascent PLC

We now present a brief description of the shift in productive activity of one PLC in their first semester working together, illustrating the use of the PLC Inquiry Framework. This group consisted of seven teachers who primarily taught Trigonometry and Algebra II. Tara, who was much younger than the other experienced teachers, was selected by the school principal to be the facilitator for having previously generated significant gains on district and state assessments.

For the first few weeks, the teachers completed mathematical tasks and discussed classroom questioning strategies for these activities. Almost all teachers participated in discussions about these tasks and contributed to generating questions to ask their students. However, their participation was more characteristic of routine engagement rather than inquiry as their responses mainly took the form of answering the facilitator's questions without being reflective about the content or purpose of the discussion. After the first PLC meeting on classroom questioning, Tara, asked the other teachers whether they had changed their questioning techniques in their classes:

Stacey: I think I did ask my students to explain the process why the vertical line test.

Clarisse: I don't know if I changed anything, I question them a lot already.

Ginger: I question a lot because I want them to know the reason … I do that a lot.

Many teachers in this group felt they were already asking students good questions and were not learning anything new in these meetings. They did not take questioning as problematic, and there was a noticeable resistance in discussing questioning techniques. During this time period, the teachers expressed that they did not understand or appreciate the purpose of their weekly meetings. Other teachers were defensive about their own teaching and revealed in interviews that felt they were "insulted" when teaching strategies were suggested. For example, Hannah commented in the interview,

> Some things I have been really annoyed with, because I feel like...it seems at the beginning, was the biggest waste of time, but maybe it was just to get everyone caught up to the same level, cause we all started at different places. I just felt insulted that they thought I did not know how to ask my kids to say why and explain why you say this... I do that! And so we spent hours and hours in our PLC talking about that and we just like, we already do this! And then, it got better in the class.

The teachers appeared to lack ownership over the group's activities and frequently asked "What do ***they*** want us to do?" (referring to the project personnel) as evidenced when Tara asked the group, "See how hard that was for us to describe it without using words *rate of change*, *speed*… I guess what they are trying to get at is, could your students do that?"

During the first half of the semester, the group was participating but did not feel their activities were personally useful. Thus they were predominately non-reflectively engaged. Tara facilitated the PLC in a way that allowed other teachers to participate in routine ways. For example, she would often ask a question and expect each of the teachers to respond one-by-one, communicating directly back to her with little group interaction. This form of participation was typical of the early sessions for this PLC, and the group was rarely observed to take an issue as problematic. The teachers expressed that they were mostly doing what they felt the project personnel were asking them to do and felt frustrated and disengaged.

After a few of weeks, Dee, an experienced teacher and researcher on the project who perceived the group's engagement as non-reflective, decided to attend their meetings. She began to participate in the discussions without explicitly taking on a leadership role, but was able to progressively help the teachers appreciate the objectives of the activities and provide insights about the goal of the project. She spent time with each teacher individually and listened to their comments and concerns. After Dee generated trust and confidence among the teachers, they expressed that they felt more respected and valued. They started to acknowledge that they had room for improvement as teachers and viewed the project as personally beneficial. Dee modeled effective inquiry in the various PLC activities and provided the necessary conceptual resources for the group to engage successfully.

Dee's attendance coincided with the group's lesson study for which she provided significant input and assistance. She helped the teachers focus the lesson study on their particular felt needs, allowing for their contribution. She also performed many of the mundane tasks needed for each meeting, allowing the teachers to be involved at a more reflective level. She was able to defuse the resistance among the more experienced teachers which in turn allowed the facilitator to more effectively direct the focus of meetings. In contrast to the beginning of the semester, the teachers took various issues about the lesson development and evaluation as problematic, and were no longer interacting through brief question and answer turns. By the end of the semester, all teachers commented that they enjoyed and learned from the lesson study activity and viewed Dee as a critical resource, authority, and source of coherence in the PLC meetings, as Clarisse said,

> When we started the PLC, it just seemed so… disjointed. We were doing this then we were doing this, and it was like a flow, and it wasn't like a pattern... I didn't know what

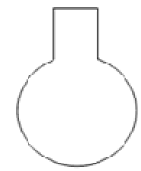
> the end product looked like. I didn't know what I was supposed to be doing or changing. I knew we were doing activities in class but that did not always transfer to what I was doing in my classrooms, so it was kind of frustrating. I mean I was feeling it was like… kind of chaotic… Even the facilitator was not even helpful... As a facilitator, she was not even facilitating, it was just chaotic... I think your facilitator should know what direction they should go in and I don't feel we really knew that, and I was not really sure if she knew that... and what the goal was... It was frustrating to me.... Dee came in to our group and she was really helpful. Like when we reached the point of total frustration, she really gave us a lot of guidance. Now we felt like we know what we were supposed to do.

The majority of teachers described Dee as the de facto facilitator, mentioning that Tara often did not know how to answer their questions. When asked for feedback on the project, for example, Ginger responded, "I mean I enjoyed it. I think I need to see more how it can stick together, and I like more concrete… give me an example, not of just a lesson plan... Dee was really our facilitator, I mean… honestly. She was excellent, she had excellent ideas."

Unrealized Potential in a Nascent PLC – A Contrasting Case

This section provides an example of a PLC session that, in contrast to the previous case, was inquirentially engaged in mathematical problems at the beginning of the semester but shifted to engaging in a routine manner on their lesson study at the end of the semester. This PLC consisted of 5 members including the facilitator, Jay, each teaching a section of Algebra II. At the beginning of the semester, the teachers were working on mathematical tasks and developing classroom questions to foster and assess student learning. Jay's facilitation allowed the other teachers to do most of the talking as he listened to their input and directed the group accordingly. This is exemplified by a session in which the group worked on the following problem:

Imagine the bottle shown to the right filling with water. Sketch a graph of the height of the water as a function of the amount of water that's in the bottle. Try to justify your graph without using the words faster, slower, speeding up, etc. Justify your graph in terms of the water and height.



The teachers began this session by comparing their graphs and justifying their work with meaningful descriptions of the graph in terms of the relevant quantities. All of the group members displayed curiosity about discrepancies in the various graphs and enthusiastically worked to resolve them. As each teacher discussed their graph, the other members held them accountable for providing concrete reasons for their claims, ensuring the integrity of the discussion. Members that made vague comments about their graph were asked to elaborate specifically in terms of the quantities and context as illustrated in the following exchange.

David: The amount of water that is put in… it, the height will… change, as we go. And there are three…

Ken: How much does it change?

David: That is to be determined… I think that's determined by these formulas. What your uh, how big the sphere is. I'm assuming that the bottom of this is a sphere.

Ken: How about in relationship to prior and later additions of water?

David then justified the shape of his graph in terms of sequentially added amounts of water as Ken requested. One group member was able to describe his graph particularly effectively in terms of the quantities and context of the bottle. The other group members assessed that these conceptual tools were usefulness for the given task and began trying to make sense of the graph in terms of the quantities using the same ideas. In the following excerpt one PLC member pushed to make sense of another's description of his graph.

Ray: You said something kinda interesting at the very beginning. You said it rises… the height of the water rises…

Ken: Will not rise as much for each unit of water…

Ray: At the very beginning when you put water in there, it's rising some amount. How does that change from… you know a couple… a couple more volumes of water?

Ken: Well if I add more units of water, the height changes less and less until I get to the middle of the bottle in which case the height will start changing

Ray: At the very bottom, how does that compare to the very top of the sphere right below the neck? Will those amounts of height per volume of water be the same?

Ken: Well right in this area it's going to be a little bit less then it will be right here (*marking on his graph*). So it… as you go up here the amount that it rises increases for every unit of volume of water that you put in…

The group was able to engage in an enthusiastic and reflective manner because of the conceptual resources of both the facilitator and the group as a whole. Jay had participated in facilitator training sessions which included mathematical tasks that required similar reasoning. Those experiences reinforced the needed conceptual resources for the task and provided Jay with an image of productive facilitation for such an activity. This image allowed him to recognize when to step back and let the group work together as a unit during the content activities and when to provide more direction.

A few weeks in the semester, the teachers began work on their lesson study for a lesson they all planned teach in their classrooms over a period of two or three days. They developed worksheets to guide students' activity and formulated questions they would ask during the lesson. The group worked on this lesson development for about six weeks, but after only a couple of sessions began to interact in a disengaged, non-reflective manner.

The teachers' focus shifted from trying to characterize conceptual understanding for their selected topic to routinely working through the weekly agendas. They were not reflective about the lesson they were developing or the usefulness of the questions they were constructing. The facilitator, Jay, began to simply present his own ideas rather than trying to get the group to reflect on each other's ideas. During one session for example, each teacher had completed and brought their own lesson plan. Jay distributed a copy of Ken's lesson then began reading it to the group. When he finished, there were a few seconds of silence before he asked if anyone had questions, comments, or opinions. He then picked up his own lesson plan and read from it for several minutes andsummarized,

> In other words I thought… I feel like the first worksheet is to find out what they already know. I think [Ken's] is a good explanation of what we are trying to get to. And I may be wrong…but I'm thinking, in my opinion I was thinking that the initial focus is to find out how much the students know.

Jay then asked the other teachers what they thought the goal for Ken's worksheet was. After they quickly summarize what they thought Ken was trying to convey, Jay concluded, "Okay, so maybe the focus is a little bit more like mine." He then read from his own lesson plan for the remainder of this discussion.

By the end of the lesson study, it was evident that the group was not interested in the lesson in the same way they were interested in the mathematical activities. In fact, the group members' commented they were only interested in completing what "they", meaning the project directors, wanted them to do. The project had not supported Jay to formulate an image of facilitating the development of a conceptual lesson or the entire group to develop an image of such a lesson. The teachers also anticipated students would resist the implementation of a new type of lesson in the middle of the semester, and many of the group members felt that they were already successfully able to teach and question students during lessons.

Conclusions

The PLC Inquiry Framework consists of central categories of behaviors related to teachers' processes and dispositions while engaged in Project Pathways PLCs. These categories emerged from our data analysis focused on discerning attributes of the PLCs that contribute to their productivity while working together on questions of content in their teaching discipline, student learning and thinking, their classroom practices, and their communication with each other. Consequently, the analysis shed light on the interrelationship among the project goal of fostering meaningful collaboration, productivity of the PLC, and the nature of their inquiry.

A central goal of Project Pathways was to foster *meaningful collaboration* among teachers, emphasizing long-term, scientific engagement of issues of teaching and learning in communities that deprivatize the cultural practices of teaching. The emergent categories of the PLC Inquiry Framework characterize aspects of such engagement that are observable and have been directly connected to the productivity of the communities, defined both by project staff and by the members of the communities themselves. As emphasized by Dewey, it is precisely the interactions between the conceptual tools and the problems to which they are applied that make the development of new ways of thinking possible. Specifically, these interactions are composed of the active selection and application of the conceptual tools on the problematic situation and, reciprocally, the evaluation of the tools against the problem.

In the episode in which Dave wrestled with both the contradictions between his PLC's data and his experience of the context in which it was collected. As he applied conceptual tools such as reasoning about amounts and rates of change using various representational systems, his understanding of the contradictions deepened. Reciprocally, as he applied these tools and evaluated their appropriateness and effectiveness, he found a need to draw on additional resources, and thus grew to appreciate previously unforeseen connections between his conceptual resources. Dave also took as problematic his difficulties communicating his concerns to his colleagues. As he tried various approaches to convey these concerns, he carefully listened to their responses and developed an evolving way of understanding how his arguments were being interpreted. His assessment that they were not effective led him to consider and develop additional lines of reasoning, thus feeding back to his inquiry into the problem itself. This complex dynamic was characteristic of the most productive PLCs.

We have found the PLC Inquiry Framework a valuable tool both for orienting observers of PLCs to critical attributes for their success and for evaluating and modifying the design of the project interventions. Observers of PLCs, researchers and support personnel, have used the framework to on the characteristics most consequential to their productivity rather than being distracted by the types of "pseudo community" as highlighted by Grossman, Wineberg, & Woolworth (2001). In the ongoing redesigning of the project interventions, it has been critical to respond to highly differentiated needs of each PLC to effectively support their development as a productive community. Identifying productive and unproductive characteristics of a group's interactions has been crucial to this process and allowed for rapid modification of the supports provided. Our ongoing research aims to further characterize necessary and effective supports for teachers under various conditions identified through application of the PLC Inquiry Framework.

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