High School Teacher Change, Strategies, and Actions in a Professional Development Project Connecting Mathematics, Science, and Engineering

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Abstract - **Project Pathways, an NSF Math Science Partnership professional development project, uses four semester-long courses and professional learning communities (PLCs) with the goal of enhancing teacher knowledge, skills and practice. The unifying concept of function is applied to promote conceptual competence in core content subjects and key problem solving processes. Modules integrating math, science, and engineering are delivered in team-based studio labs complemented by associated PLCs. The research question here is, "What is the effect of a function-driven joint high school math/science teacher based professional development project on teacher change, strategies, and actions?" The relevance is that it addresses issues about student math and science achievement and the STEM pipeline. Teacher change was evaluated using qualitative analysis of post-class question responses for five factors: creating a math/science teacher culture of collaboration; deepening content understanding by use of function; integrating math, science and engineering; developing inquiry strategies and materials and; promoting metacognition on student thinking for effective learning. For 27 responses, 24 showed positive change shown by shifts for one or more of five factors. Overall, the project created function-infused courses linked with multifaceted, synergistic PLCs that facilitated teacher change, strategies, and actions for improved practice.**

Index Terms – Professional learning communities, student thinking, teacher metacognition, and teaching modules.

INTRODUCTION

Project Pathways is a National Science Foundation Math Science Partnership (MSP) professional development project, which targets mathematics and science learning and achievement in grades 9-12 by connecting math with context-rich content and problem solving processes in science and engineering. Teams of math, science, engineering and education faculty are partnering with community college master teachers to generate instructional sequences of modules for four courses for secondary mathematics and science teachers and their students. The courses are promoting conceptual competence in core content subjects and key problem solving process behaviors in mathematical problem solving, in scientific inquiry, and in engineering design. The understanding of mathematical function as a unifying concept is applied throughout the courses. Conceptual competence in core content subjects and problem solving process behaviors is promoted using team-based, inquiry learning pedagogy with contextualized content in MSP-created modules. The unifying concept of function, developed in the initial Mathematical Functions and Modeling (MFM) course, was integrated into science and engineering topics in the subsequent courses. The function concept was emphasized through teachers' articulation of the language of mathematics including change and rate of change and was used to develop mathematical relationships embedded in science phenomena in various disciplines. Professional learning communities (PLCs) are supporting teachers in adapting their new knowledge and instructional approaches to their own classroom practice by engaging them in deep reflections on their instruction and their students' thinking and learning. Math, science and engineering are connected by knowledge and use of function. Function was developed in the MFM course and integrated into science to describe phenomena in the courses, Connecting Physics, Chemistry and Mathematics (CPCM) and Connecting Biology, Geology and Mathematics (CBGM). It is then applied to design projects in the form of predictive tools about science phenomena in the course, Connecting Engineering with Science and Math (CESM). Examples of these connections include utilizing function in the Universal Gas Law and also Newton's Laws as applied to the design process in the Hot Air Balloon Project.

The structure of Project Pathways offers the opportunity for high school math and science teachers to team together in a collaborative culture of professional development activities both as students in MSP courses as well as teachers in PLCs. In so doing teachers from the math and science disciplines are able to experience quality modeling of math and science pedagogy, not only by course instructional leaders, but also by their own team members. The nature of math-science integration and implementation of enhanced knowledge, understanding, and skills will differ in math and science classroom practice, but there will be an underlying understanding of the complementary nature of math and science implicit in the pedagogy modeled in the project's courses. This linkage and integration of math and science has the potential for synergistic impact on student learning in both math and science and should be reflected in student performance. The project's four courses will facilitate connections between math and science and engineering.

The connections address the project's thrusts, first presented in the original NSF proposal, which are embedded in the courses and associated PLCs and include the following. One thrust is the creation of a sustainable culture of collaboration of math and science teachers in PLCs. A second thrust is the application of conceptual understanding of mathematical function for deepening the knowledge and the problem solving process skills in math, science and engineering. A third thrust is the integration of math and science through: science and engineering contextualization of math content and processes; through enhanced mathematization of science phenomena, and through use of mathematical representation of science phenomena as predictive design tools in engineering design processes. A fourth is the development of classroom strategies and materials for inquiry learning activities. Finally a fifth thrust is promoting teacher metacognition about student knowledge, thinking, and behavior in inquiry activities for guiding student learning.

In summary, this paper reports on the qualitative analysis of end-of-course question responses related to five MSP thrusts which include: collaborative culture; function-driven problem solving skills; contextualized integration of math, science and engineering; strategies and materials for inquiry learning; and metacognitively mediated student inquiry learning. The question was a final reflection in the second course, CPCM, which followed the conceptual development of function in the initial MFM course. Both courses lay the foundation for mathematization of science phenomena as engineering design process tools for the final course, CESM. The research question for this work is, "What is the effect of a function-driven joint high school math/science teacher based professional development project on teacher change, strategies, and actions?"

BACKGROUND

The project approach for improving high school student math and science achievement has been use of inquiry learning in MSP courses and PLCs for promoting teachers' deep understanding of foundational STEM (science, technology, engineering, and math) concepts and the processes and the connections between them. Research shows that STEM teachers in U. S. schools lack content knowledge and mastery of subject-related pedagogy that enables them to teach content most effectively [1]. They also lack a sense of the connections among concepts that reveal mathematics as an internally logical and coherent system of knowledge [2]. This forces teachers to use lectures to deliver content, which emphasizes procedure over engagement. This deters hard-thinking explorations that help develop critical minds with the capability to deeply understanding mathematical, scientific and engineering concepts [3]. In a high minority-population state like Arizona, superficial teaching of STEM subjects disproportionately undermines STEM learning of minority and low-income students [4].

Mathematical function is the unifying concept of the courses and is often used by scientists and engineers as a mathematical model of change. Here, the teachers explore the concept vertically across grade levels and horizontally across science applications (biology, geology, physics, and chemistry) and engineering design. Understanding function is essential for students' future success in calculus [5] and is critical for retaining minority and female students, whose progress in math and science often bogs down at the precalculus level. The function concept is so complex that even quality students exhibit weak and disconnected understanding of it [6], the primary cause of which is that teachers also have a weak understanding of function [7] which forces them to take a procedural approach to teaching functions [8]. Carlson, et al. [9] have developed guiding frameworks for defining and assessing students' function knowledge and emerging understanding.

Modules in each course feature examples of function as mathematical models of change scientists and engineers use to quantify reproducible patterns of phenomena in natural and physical science and then apply them as predictive tools for phenomena engineering design. For example, in biology a student might model impact of an invasive plant in an ecosystem as a function of its average rate of growth per year. In engineering design, a student could link function in rate of velocity change in Newton's Laws to describe upward acceleration in the Hot Air Balloon Design Project. Science and engineering projects not only provide opportunities for mathematization of phenomena for science teachers, but also provide math teachers opportunities to learn of rich, new contexts for framing math inquiry activities. Sharing instructional approaches between math, science, and engineering is yielding new ways of making foundational ideas relevant and accessible to students. Accessibility is also enhanced by contextualized content delivery with team-based inquiry learning discussed next.

Inquiry-based learning uses strategies that engage students in contextually relevant problems related to real-life experiences. Incorporating inquiry-based learning skills into laboratory activities or classroom discussions can have significant educational benefits. In inquiry learning asking questions, hypothesizing, formulating ideas together and explaining are important aspects of discussions in a team based environment [10]. For example: inquiry used by practicing teachers improves teaching skills [11]; collaborative problem-solving changes the roles of teachers to facilitators and students to problem solvers [12]; and team-based activities and discussion lead to critical question posing and creative thinking [13]. Patrick and Middleton [14] stated that success in inquiry activities "requires cognitive, metacognitive, motivational and collaborative engagement that comprises self-regulated learning." Such deep learning is a key aspect in developing the ability to achieve "far transfer" of problem solving knowledge and skills to new and unfamiliar contexts and situations [15].

This is particularly important when using the mathematical description of physical phenomena as predictive tools to engineering design processes and systems.

Contextualization of math concepts and processes through appropriate framing in science, engineering, and real-world contexts promotes motivation and access because of relevance and usefulness to the learner [16]. Recognizing and valuing individual prior experience shows usefulness and importance of math and helps the learner recognize what they can do and how to build on it [17]. Examples of mathematics in the workplace, in financial planning, and observed phenomena can connect with the students' meaning and social environment [18]. It can also change a person's views of the nature of mathematics. Rogers [19] says that contextualization "demystified the doing of mathematics . . . calling attention to mathematics as a creation of the human mind, making visible the means by which mathematical ideas come into being . . . and engaged students within the classroom in purposeful, meaningful activity."

METHODOLOGY

These results at the end of the CPCM course examine the effect of professional development connecting math with science after an earlier course of MFM which was a foundation for this second course, CPCM (and associated PLCs) taught in spring 2007. In both MFS and CPCM courses, the PLCs facilitated immediate adaptation and feedback of MSP course pedagogy in teachers' classrooms. It was desired to summatively assess the impact of these two courses and associated PLCs on the five factors of teachers': collaborative culture; mathematical function driven problem solving skills; contextualized integration of math, science and engineering; strategies and materials for inquiry learning; and metacognitively-mediated classroom student inquiry learning. To do so, written reflections of teachers from three districts (Scottsdale, Tempe, and Mesa) were qualitatively analyzed in response to the following question:

> *Think back on all the lessons in this course. What, from the things you learned, have you incorporated into your own teaching? Include the following categories in your answer: concepts from the opposite discipline (math teachers should state what science concept they are using, and vice versa), teaching methods, and reasoning strategies ("speaking with meaning").*

Analysis of teacher changes, strategies and actions with respect to impact on student learning and attitude is not yet available, but is being assessed in terms of students': course grades; performance on high stakes state math tests; and on future interest and enrollment in advanced science and math classes. Processes and procedures for obtaining, assessing, and analyzing the appropriate data have been cumbersome because of the lack of uniformity of data acquisition, recording, and extraction procedures across different school districts but should become available in the future.

RESULTS AND DISCUSSION

The data shown here is a summarization of the qualitative reflections of 27 teachers from Mesa, Tempe and Scottsdale. The results are organized into five sections on teachers': collaboration, function, inquiry, math-science integration, and metacognitively-mediated student learning. Responses for each of the factors are sampled from the 10 math and 17 science teachers – typically one math and one science teacher. Each factor starts with a short description about the factor and its impact, comments on the examples, and then the two excerpt examples. All responses were reported under pseudonyms. Generally speaking, of the 27 teachers, all 10 math teachers and 14 of 17 science teachers had positive responses on one or more of the five factors. Excerpts have been reproduced in the exact form as scripted by the teachers, and may include a variety of possible semantic, grammatical, and spelling errors. Authentic qualitative analysis requires exact reproduction of data as gathered so as to not shift meaning or expression.

For the MSP classes, the hands-on activities of equipment set up, experimentation, data collection, data analysis, and constructing the connection of phenomena mathematical function help provide a foundation for the predictive design tools used for designing, building, and characterizing behavior of hot-air balloons in the CESM course. Far transfer of conceptual knowledge from the MFM and CPCM classes and PLCs the design activities of the CESM class is promoted by inquiry based development of the Universal Gas Law and Laws of Motion in the CPCM.

I. Professional Learning Community Collaborative Culture

PLCs affect school culture and can help to create more effective schools. The shift from individual responsibility to shared responsibility can create a collaborative culture to facilitate reform [20]. In the MSP courses, instructors' modeling of content, process and pedagogy is reviewed, examined, and reflected in the PLCs. Approaches, barriers, and mechanisms of implementation of change in teachers' own classroom practice are considered in developing possible strategies for implementation. Feedback from prior experience can be used to reflect on the effectiveness of different approaches. Consequently, teachers develop ownership of change and become advocates of desired reforms. Thus, the PLCs contribute a foundation for sustainable change that extends beyond the lifetime of the MSP grant. In the examples shown below, both the math and science teachers discuss the differences about how math is presented in math versus science classes. With collaboration of colleagues from the other discipline, both math and science teachers have learned how to accommodate and take advantage of the differences to provide more effective pedagogy for their students.

Mary, a Scottsdale math teacher, in discussions in her PLC and her CPCM course, has discovered differences in how math is presented in science compared to math since numbers in science are inexact and must have their precision specified. She is using this knowledge to better connect with her students who are taking physics and chemistry. As such, she has opened up a dialogue about mathematics in science between herself and those students. This has inspired her to develop an inquiry "math" lab to contextualize a harmonic motion function with the spring oscillation activity. She says, "A big comparison of math education and science education is that in science and the real world, nothing is exact or perfect. In math we like to work with exact numbers and measurements. Over the course of the semester, I have already made references in my classes to the science concepts I've learned in CPCM. What I learned about significant figures has also been very helpful in the math classes I've taught. Knowing these concepts has made me a better math teacher because it has given me some real world connections to the math concepts that I teach. It opens up the dialogue between students that are taking physics and chemistry and me. The class has also inspired me to do some experimental activities to teach math concepts."

Christine, a Scottsdale science teacher, has been learning in the CPCM course and the associated PLC how to transport pedagogical tools from the course to her own classroom. One pedagogical approach presents multiple representations of the same data as tables, graphs, bar charts, and equations. She has successfully integrated one of the tools in her own practice in saying, "In Chemistry, we deal with energy of a system all the time. I have started to have my students use bar charts to represent the changes in energy for a system. The visual depiction of the energy really helps them to understand what is happening as the reaction or physical process proceeds forward.

From a mathematics standpoint, I have been showing my students how to rearrange the variables in an equation in order to get it set up for the unknown variable that we are solving for in the problem. I have noticed that many of the students are making fewer math errors with their calculations. Now that I am teaching the Gas Laws, I will require my students to show proportional reasoning as well as the gas law equation approach to solving the problems. I really like the fact that setting up the various ratios will help me confirm whether or not they have grasped the relationship between the different variables (volume, temperature, pressure, and amount) for a gas."

II. Mathematical Function to Deepen Problem Solving Skills

Math teachers in the MSP are finding that contextualization of the math with science helps clarify and deepen the understanding of the concept of function as shown with the example here. For science teachers there has been increasing use of the concept of function in their classes as demonstrated by increasing mathematicization of science phenomena. This even sometimes simplified and made more clear the science or was the only way to understand the science, as is shown with the example below. Some science teachers are also using functional relationships of the phenomena studied to develop controlling equations to generalize parameters that describe physical relationships.

Paula is a Mesa math teacher who has found that in using the context of the physics of motion from the CPCM course has helped her understand better and explain better the math that she had been teaching. She says, "Overall, I feel that I have gained so much deeper understanding of the concepts covered in this course that I truly am a better teacher. With the physics background I gained from this course I am planning to incorporate "labs" into my math classes. I have found that actually seeing how ideas of distance, time, and rate were related and discovering those relationships helped me understand so much more."

Barbara, a Scottsdale science teacher, is enhancing math-science integration because she realizes that, for some phenomena, the only way to understand is through the mathematics. She says, "To understand the science of EM waves and light one needs to comprehend the mathematics behind it. The wavelength is inversely related to the frequency of the wave. Waves are "in phase", when they coincide peak to peak and trough to trough, and produce a bright spot. These can be produced when the difference in path length is an integer multiple of the wavelength of light. For waves to be "out of phase" the waves need to coincide trough to peak and produce a dark spot. Then the mathematics formula has to have a path length of an odd multiple of half the wavelength. Changing the path length results in the waves coinciding differently, resulting in a bright or dark spot. This is an excellent example of how science and mathematics work hand in hand to explain a concept. The math formula can be manipulated to receive the result you want in science or the science can be explained by understanding the mathematics."

III. Integration of Math and Science through Context

Math and science can be integrated through context. As discussed earlier, contextualization of math concepts and processes through appropriate framing in real-world contexts promotes motivation and access with a concrete platform for discussing abstract math concepts. This is shown below where a special education math teacher has used a context of Archimedes principle to develop the mathematics and associated terminology based on the physics of motion. Likewise, an earth science teacher has discovered real world contexts as a setting for the mathematics that describes earth science phenomena in different situations.

Hannah, a Tempe special education math teacher, contextualizes her math with science by using graphs to tell a story, in particular, the graph and math of the realistic story of Archimedes taking a bath. She has effectively engaged special education students by contextualizing and, by having inquiry discussions; she has provided access and improved understanding of functions concepts. She says, "We did this without setting up a scale, so that students could just draw a line showing increase, constant, and decreasing volume of water in the tub, as we filled the tub with water, turned off the water, put a man in and out of tub, and the water level decreasing when we pulled the plug over a period of time.... In doing this lesson, students were able to speak in meaning with terms of speed, average speed, velocity, average velocity, acceleration, and distance, and displacement."

Hilda, a Scottsdale science teacher, sees many opportunities to integrate mathematics into her earth science classes through students' discovery of relationships related to contextualization of math for "real situations". She says, "I have already incorporated several things from this class into my own teaching. I now see more opportunities to incorporate math into my earth science class especially.... I help to facilitate and guide their thinking, but let them discover the relationships. This aids in their understanding and helps them to make the content knowledge their own."

IV. Strategies and Materials for Inquiry Learning Activities

Many math teachers promote inquiry by mathematizing physical phenomena through various labs such as playing a guitar or tossing a ball. Labs and discussions promote inquiry and engage students to enhance their learning. Also, some math teachers had never collected and analyzed data, but developed the skills and self confidence to work with "dirtier, real-world" data and design and implement real-world science contextualization activities in their classrooms. Some science teachers also modified or developed new inquiry-based science lessons or labs that incorporating more math. In science, mathematization of physical phenomena, such as the Gas Laws, provides a strong foundation for the use of the predictive engineering tools used for designing, building, and characterizing behavior of hot-air balloons in the CESM course.

Dan, a Mesa math teacher, wants to implement a "math" lab into his classes in the future. Dan plans on using a guitar context for developing an inquiry lab that would provide a physical representation of a proportion function. He says, "One lesson that I found to be very interesting was the wavelength of a guitar string. I would love to implement this lesson in my math classroom when I am teaching about waves or proportions. The students can discover physically what is happening to the wavelength and see a physical representation of a proportion."

Christine, a Scottsdale science teacher, is integrating math and science by using inquiry to study proportionality concepts to mathematicize the Gas Laws. She says, "Now that I am teaching the Gas Laws, I will require my students to show proportional reasoning as well as the gas law equation approach to solving the problems. I really like the fact that setting up the various ratios will help me confirm whether or not they have grasped the relationship between the different variables (volume, temperature, pressure, and amount) for a gas."

V. Teacher Metacognitively Mediated Student Learning

While metacognition has been cited as a key principle that students should employ for more effective learning, it has been suggested that teachers would also benefit from a similar strategy during inquiry learning [21]. With different individuals, learning styles and learning skills need to be recognized and addressed in the classroom. A clear definition of learning goals is necessary in order to utilize the most effective pedagogy which is dependent on the various types of students found in the classroom. Choosing or inventing an effective metacognitive strategy is key to achieving a more effective inquiry learning classrooms. In the examples below both the math and science teachers have employed metacognition to mediate the inquiry learning in their classrooms.

May, a Tempe math teacher, developed an engaging, hands-on, inquiry "math" lab with graphing calculators to develop a mathematical expression for describing the function for position-time relationship for the context of a vertically tossed ball. She says, "I was able to incorporate the use of vertical motion as a real world phenomenon represented mathematically by a quadratic function. Students conducted experiments and collected data to find how high a ball was thrown into the air. This provided motivation for the students and they were actively engaged in the lesson."

Frieda, a Scottsdale science teacher, will further integrate math and science in emphasizing what the data are saying about the mathematics of the science in classroom experiments. She says, "As a science teacher, the concepts I have tried to use more often in my class include: truly understanding what the mathematical data is saying about the experiments conducted in class, knowing that there is more that one way to solve an equation and allowing the students to know all ways to "attack" a problem, and finally using the mathematical calculations to support or not support the hypotheses (where applicable)."

Summary and Conclusions

Overall, the data provide evidence that the CPCM course and associated PLCs have promoted a positive shift in teacher change, strategies, and actions in the five thrust areas: collaborative culture; function-deepened problem solving skills; contextualized integration of math, science and engineering; strategies and materials for inquiry learning; and metacognitively-mediated student learning. While the CPCM course has provided a common hands-on learning experience for the math and science teachers, the PLCs have been able to create a community of collaboration with shared goals, experiences, values, and approaches to implementing reform in their own practice. This cultural change has made possible by implementing various classroom strategies such as an emphasis on the concept of function as both as a key to understanding math as well as a key to understanding the functional quantification of science phenomena. In some cases functional mathematics may be the only way to effectively understand some topics in science. The math teachers described the integration of math and science through the contextualization of the mathematics they were teaching. The science teachers found that their understanding of function deepened with the broader diversity of contexts in which function was used. Inquiry learning was promoted by the math teachers through contextualization because of the familiarity, relevance and usefulness of context to the learner which helped clarify the mathematics that was being applied. For the science teachers the greater mathematization of phenomena helped deepen their understanding of the concept of function in ways that allowed them to use more math and new ways to use math in their teaching of science. Both math and science teachers described ways in which reflections helped devise effective strategies for integrating math and science for promoting inquiry and student learning.

Overall the shifts toward greater integration of math and science were substantial and actually represented change, or intent to change, in the classroom practice of all 10 math teachers and of 13 of 17 science teachers. For almost all teachers, a shift was observed away from an image of good teaching as "explain and telling" toward an image of good teaching as "creating learning environments that promote meaning making, inquiry, and construction." This promotes deep understanding of content and process necessary to achieve far transfer of mathematicized phenomena for application as predictive tools in the engineering design process. While the MSP and its courses will finish in time, the dialogue, strategies, and manifestations in classroom actions can be sustained through a culture of collaboration if school leadership provides the means for a progression of PLCs into the future. In fact, one of the school districts is currently implementing standing PLCs for math and science teachers and it is hoped that the effects will be sustained by other districts also doing so.

ACKNOWLEDGMENT

The National Science Foundation supported this work via Project Pathways MSP Grant 0412537.

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