Interventions that Involved STEM Disciplinary Faculty in Deepening Teachers' Mathematics Content Knowledge

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The Summer Institute

During the summer of 1999, 22 middle and secondary teachers participated in the integrated science and mathematics institute. Of these 22, 10 had previously participated in an integrated science and mathematics program at WSU. The teacher participants had diverse backgrounds ranging from 2 to 35 years of teaching experience and from no professional development experience to master's degrees. Additionally, the areas in which the teachers specialized were quite different: four special education teachers, four mathematics and four science high school teachers, and 11 middle school teachers. The three districts involved were a large urban district, a suburban district, and a smaller urban and rural mixture. Student populations ranged from 75% African American students to 85% Caucasian students. These districts were chosen because they are local to the university, and WSU's preservice teachers are often placed with these districts for field experiences.

The summer institute was intensive with 72 contact hours of class over a 4-week time period, meeting 8 hours a day for 3 days a week. We immersed the teachers in inquiry-based learning environments, in which they worked on integrated science and mathematics units in cooperative groups of three or four. The general structure of the institute involved teachers spending two thirds of each day working on content units and the remainder of the day considering pedagogical issues and developing such units for use in their own classrooms.

Two different cooperative groupings were used. For the science and mathematics investigations, teachers were grouped heterogeneously with the requirements that the teachers in the group could not all teach the same grade level, or be in the same district, or teach the same subjects. For the development of units, cooperative groups were formed by same, or similar, grade-level teachers, since these teachers shared similar curricula and were often from the same district. Including both elementary and secondary science and mathematics teachers within the same groups for content investigations effectively expanded the resources and expertise available to groups in both content and pedagogical knowledge. Rich discussions resulted from these heterogeneous groups, often involving topics of vertical curriculum alignment and effective pedagogical strategies. Heterogeneous grouping typically developed mutual respect and cooperation among the different grade level and topic teachers.

To best model standards-based integrated science and mathematics teaching practices, we team-taught the institutes. In this way, teachers experienced teaching from both the science and mathematics perspectives and gained pedagogical knowledge of both disciplines. Master's degree program students who were also secondary science and mathematics teachers helped facilitate the institutes. These "resource" teachers provided real classroom connections that aided participants in transferring the institute experiences to the precollege classroom.

Due to the diverse backgrounds, teaching assignments, and teaching environments of the teachers, the content of the institute was matched to grade 4-12 strands of the science and mathematics standards, with topics chosen for their importance and integration aspects. Content investigations started with the most fundamental concepts, usually encountered in the earlier grades, and built up to

the concepts and applications of the upper grades. Even though the content was consistent with grades 4-12 standards, the teacher participants analyzed the content at an adult level in order to develop the conceptual understanding necessary to teach effectively.

We used a combination of commercial curricula and curricula we designed. Commercial resources included *Mathematical Modeling in Our World* (The Consortium for Mathematics and Its Applications, 1998a) and physics education materials (Arons, 1997; McDermott, l996). The integrated science and mathematics units we designed ourselves were adapted from preservice teacher course activities (Basista, 1998a, 1998b). When designing the units, we took great care to maintain conceptual development for both disciplines. Indeed, we chose many of the specific science and mathematics topics not only for their importance in the teachers' curricula, but also because the topics lent themselves to a high degree of integration. In every case, we made no assumptions about the backgrounds of the teachers. Each unit started with the most fundamental concepts and built teacher understanding from that basis. Since 1997, we have utilized units such as motion and graphing; shadows and proportional reasoning; and simple machines and proportional reasoning. Refer to Table 1 for the topics covered in 1999.

The integrated science and mathematics units were of a guided discovery format, with facilitator checkpoints included after conceptually connected sections. At the checkpoints, we utilized questioning techniques not only to deepen the teachers' understanding, but also to model effective questioning strategies. At these checkpoints, we often discussed pedagogical issues related to teaching the material in grades 4-1 2 classrooms. We assigned daily homework over the sections completed to help solidify the teachers' understandings of the content and to provide further examples of applications of the concepts.

The pedagogical issues addressed during the institutes related directly to the standards, their implementation, and assessment. These topics included comparisons between inquiry and traditional environments, assessing students' prior understandings, methods of modifying and/or developing inquiry-based activities, cooperative learning techniques, development of in-depth conceptual understanding, development of problem- solving skills, integration of science and mathematics, reflection on one's teaching, and authentic assessment techniques. For a sample of pedagogical content covered in the summer institute, see Table 1.

About halfway through the institute, the class was divided into groups of teachers who taught similar grade levels so that they could develop integrated science and mathematics units for use in their classrooms. At this point, the teachers began to apply the science, mathematics, and pedagogical content knowledge they had acquired during the institute to their own classrooms. During the final two days of the institute, the teachers team-taught lessons from their developed units for the class and received peer and instructor feedback.

Academic Year Support Activities

We visited the teachers' classrooms three times during the academic year to observe them, to model teaching methods, and to provide feedback about their teaching practices. During the academic year, the teachers attended three workshops, in which they shared the results of their efforts. During the workshops, pedagogical issues and district issues were frequently discussed. We encouraged teachers to maintain contact with us through phone and email.

Throughout the academic year, the teachers built portfolios documenting their efforts in modifying their teaching practices. These portfolios included lessons they had taught in their classroom, together with reflections, student feedback, and results. Teachers documented their efforts in implementing inquiry and cooperative teaching practices, developing their students' in-depth content understanding and problem-solving skills, and utilizing forms of authentic assessment.

Table 1
Summer 1999 Topics

Science Content	Mathematical Content	Pedagogical Content
Shadows	Proportional reasoning	Science and mathematics standards
Measuring heights and distances	Geometry	Inquiry
Levers	Multiple representations (graphs, diagrams, symbols)	Integration of science with mathematics
Hooke's Law	Logistics modeling	Developing problem solving skills
Population growth	Modeling vs. problem-solving	Authentic/alternative assessment
Population growth	Exponential growth	Cooperative learning
		Modifying and developing inquiry lessons
		Questioning techniques
		Reflective teaching practices
		Facilitating inquiry lessons

Excerpted from Geer, C. H. (2001). Science and mathematics professional development at a liberal arts university: Effects on content knowledge, teacher confidence and strategies, and student achievement. *Proceedings of the 2001 Annual International Conference of the Association for the Education of Teachers in Science*.

Teachers could choose among five science courses and five mathematics courses. Each weeklong course involved 30 classroom contact hours. Sixty-seven percent *(n=47)* of the teachers took three or more courses and focused on either mathematics or science. The intent of the courses were to broaden the teachers' science and/or mathematics content knowledge and, at the same time, demonstrate how mathematics and science content can be taught without lectures or rote memorization. The courses addressed national, state, and district standards and connected them to the science and mathematics content being taught. Many of the activities had a real world context so that the teachers could see the application of the science and mathematics concepts but more importantly they could transfer this learning into their own middle school classrooms. Middle school students have started to develop life aspirations, and are beginning to see themselves applying the information they are learning in school (Hanley-Maxwell & Collet-Klingenberg, 1997). Making these connections was important because often teachers are unable to transfer their content knowledge to the classroom.

The content of each course was not designed to be a comprehensive curriculum of all the concepts that a teacher would need to know; rather, it was an in-depth review of a few topics. The content was taught at the college level so that teachers developed a greater understanding of the concepts which would enable them to design higher level questions, respond to students appropriately, and develop different teaching episodes in their own classrooms.

With this framework in mind, the professors approached the content for their courses in non-traditional ways. The courses were all taught using a hands-on, interactive type approach. For example in the mathematics course that focused on concepts in probability and data analysis, teachers and faculty met at a large local cemetery where participants were assigned to four groups of six or seven. Each was given a worksheet and asked to roam through the cemetery, finding thirty gravestones, ten for the individuals who died before 1900, ten for those whose deaths occurred between 1900 but before 1950, and ten with deaths since 1950. The teachers recorded the year of birth and death for each gravestone. The instructions caused the samples to be as random as possible. For example the participants were to go in different directions and no more than one stone was to be observed from any family group. The groups then had at least sixty pieces of data from each of the time periods. Data were collected in the morning, then the groups returned to campus to combine their information and create reports using the data The groups were assigned methods for analysis of the data.

- Group A found the mean, median, mode, and midrange for the ages at death for each of the death-year groups,
- Group B made a scatterplot with the year of death on the horizontal axis and age on the vertical,
- Group C made histograms and stem-and-leaf-displays for each of the three categories,
- Group D made box plots for each of the three death-birthdate categories.

All were asked to report on the question, “Does this indicate that people are living longer?” Each group prepared a report answering this question both in written form and as a presentation. All members of the group were required to have a role in the oral presentation. Groups were encouraged to employ methods such as multimedia presentation software to present data, the internet to perform searches for documents that would support their position, and spreadsheet software or graphing calculators to do the analysis. Group presentations were given during the afternoon.

It must be noted the Arts and Sciences faculty worked with the science and mathematics teacher educators to learn about appropriate teaching strategies and needs of the K-12 teachers. Many of the faculty were already using (a) collaborative groups, (b) approaches that were inquiry based, and (c) manipulatives and hands-on materials rather than a lecture approach. The institute could not have been implemented without their efforts and different approaches.

In each course, different materials were provided so teachers were able to recreate similar lessons back in their own classrooms. The teachers were given extensive handouts of activities, experiments, resources, and standards. The course materials included items teachers could purchase at grocery, hardware, or pet stores. By using these materials, teachers realized that they did not need sophisticated equipment to learn and teach these subjects. In addition, urban districts have minimal budgets to purchase equipment so the types of items we used were inexpensive to purchase. Middle school supplemental texts that focused on specific topics and concepts addressed in the courses were purchased for the teachers. The courses also incorporated field trips to community resources such as the Natural History Museum to study local geology; the Cincinnati Observatory to learn about telescopes and planetary motion; the Krohn Arboretum to study plant diversity; and a county park to collect fossils.

Technology was utilized and integrated into the courses. The teachers used technologies such as graphing calculators, spreadsheets, databases, and Internet resources to accomplish goals of the courses. Professors used a variety of assessments in their courses such as daily journals with focus questions, problem solving assignments, development of middle school lesson plans which incorporated concepts learned during the courses, daily concept maps, and peer teaching of middle school mathematics and science lessons. The facilitators believed strongly that teachers should be treated as professionals and receive compensation for their time and effort. To support this notion, each teacher received $100 worth of materials and books, one semester credit how, and $100 stipend for every course.

Excerpted from Sowder, J. T., Phillip, R. A., Armstrong, B. E., & Schappelle, B. P. (1998). *Middle-grade teachers' mathematical knowledge and its relationship to instruction*. Albany, NY: State University of New York Press.

A brief summary of the seminars over the 2-year period is provided so that the readers will have some understanding of the mathematical content to which the teachers were exposed and how they responded to the content.

An introductory meeting in the spring of 1992 was intended to acquaint the teachers with one another and to give them an indication of what to expect from the seminars, and to give us an indication of what to expect from the teachers. During the session, the teachers were given an excerpt from a lesson on fractions (Borko et al., 1992). In the ensuing discussion, one teacher said:

> Maybe I'm way off the wall, but I don't teach kids to flip numbers upside down.... So we review multiplying fractions….Then I put up a problem with division. (The teacher wrote a division problem on the board and drew two large Xs through the fractions while reciting the following.) I say, "Follow these lines and multiply, and you got your answer. Just go "I hate math; I hate math. Boy! Do I really hate math!" (See chapter 8 for more detail.)

The other teachers responded positively to this method. They felt that teaching fractions was extremely difficult; any "gimmicks" would be useful. They indicated that they did not think it was possible to "teach fractions with understanding," and some also used Explorer calculators for multiplying and dividing fractions. They felt that students' demands for the answers prevented them from teaching conceptually.

Year 1. In the fall of 1992 we held 2 full-day seminars for the teachers. We began by discussing data on how children compare decimal numbers (from Resnick et al., 1989), then worked on place value with decimal numbers via the Blocks Microworld (P. Thompson, 1992). In the afternoon of the first day the teachers completed the Content Knowledge Assessment instrument. We made copies of the completed tests and discussed them among ourselves in terms of the areas on which we should focus our efforts. The tests were returned to the teachers unmarked, and the second day was devoted to discussing the items on that test. The teachers became very involved in considering their own responses and those of the others, then thinking about how their students would react to some of the items. Some of the items had been used with students (Armstrong & Larson, 1995), and the ways in which students thought about those items and solved them were discussed with the teachers. (When relevant, each teacher's work on this assessment is discussed in the individual case studies.)

For the remainder of the year, approximately half the seminars were presentation-focused—that is, a researcher prepared a presentation based on research with children. The presentations were informal, and there were questions and discussions throughout the presentations. When the presentations were made by visiting researchers from outside the university, a few additional teachers were invited, so that the audience was approximately a dozen. (The presentation-based seminars were substantially the same as the written versions of the presentations appearing in

Providing a Foundation for Teaching Mathematics in the Middle Grades [J. Sowder & Schappelle, 1995] as chapters by Armstrong & Bezuk, Harel, Kieren, Lamon, Mack, J. Sowder, L. Sowder, and P. Thompson.) The remaining seminars focused on follow-up discussions of these presentations, on discussions on topics selected by the investigators on the bases of their knowledge of the teachers' content understanding, of results of tests and interviews of the students of the teachers, and of questions raised by the teachers. (A more detailed presentation of the teacher interactions and struggles to understand the content of these seminars is presented in chapter 4 and also in J. Sowder & Philipp, 1995.)

The first two seminars were intended to lead the teachers to see the value of sense-making as part of the enterprise of teaching. A presentation on rational number sense led to practice with mental computation and estimation and to examination of sense-making with operations and algorithms.

The next four seminars focused on developing the teacher's understanding of fractions and fraction operations. Presentations by Mack, Armstrong, Bezuk, and Kieren provided the teachers with research-based ways of presenting critical ideas about fractions and fraction operations. Examples of students' thinking and working with fractions challenged the teachers to think about their role in teaching fractions in meaningful ways. The fourth seminar was devoted to discussion of the results of the teachers' students' work on the Fraction Understanding Test (provided in Appendix F). The items tested for conceptual understanding rather than algorithmic skill. The teachers were surprised and distressed with the results. Although they recognized that they were not responsible for the poor performance (the tests were administered after students had been in their classes for less than 2 months), they also realized that until this seminar they had little comprehension of what their students knew and did not know, thus making it difficult for them to base instruction on students' knowledge. (This seminar was summarized and analyzed in Armstrong, Philipp, & J. Sowder, 1993.)

A more holistic look at both whole number and rational number operations was the subject of the presentation "Addressing the Story-Problem Problem" by L. Sowder. He discussed the connections between the operations and the real-world applications, focusing on what elements in a situation lead to choosing the correct operation.

The next three seminars were informal; they focused on critical incidents in the teachers' own classrooms and on discussion of the previous presentations. The teachers compared ways that their own planning for instruction on fractions was changing.

In the two following seminars we turned to the topic of proportional reasoning; the discussion was based on a presentation by Lamon. Proportional reasoning as multiplicative reasoning was discussed in some detail. These seminars led into Harel's presentation in which he outlined students' progress through additive reasoning into multiplicative reasoning. The final presentation of the year, by P. Thompson, focused on quantitative reasoning in both simple and complex situations.

For the closing seminar of the first year we chose several transcript excerpts from the seminars during which teachers had struggled with mathematical concepts and had finally came to a deep understanding of them. The teachers were given the assignment of reading excerpts and

providing written reactions to them at a later date. To set the stage for this assignment, the investigators each earlier wrote reflections on the year's work and shared them with the teachers at this seminar. For the remainder of the seminar, the teachers talked informally about what they had learned and how they had changed over the course of the year. The conversations focused on the seminars, our classroom observations, their own planning and insights, and their classroom interactions with students.

Year 2. During Year 2, several of the topics introduced during the Year-1 seminars were revisited, sometimes through discussions of (sometimes videotaped) segments of the participating teachers' classroom rational number lessons that had been observed by the researchers and sometimes through revising the papers written by the presenters of Year 1. The first seminar of the year was devoted to eliciting individual teacher reflections, partly to determine ways to provide seminars of most benefit to the teachers at this stage in their participation in the project. Teachers spoke about their mathematica1 goals for the year, their mathematical expectations for their students for the year, their roles as teachers, perceived obstacles in teaching mathematics, the growth of students from additive to multiplicative reasoning, changes they were making or would like to make in their mathematics teaching, and what each hoped to gain from the project during the coming year.

In seminar discussions of observed teachers' classroom lessons (sometimes with videotaped segments presented), the importance of consistently relating the part to the unit was an issue in both the fractions and decimal lessons being discussed; all of the teachers recognized this as an issue in their own classrooms. Issues related to the use of models for rational numbers also arose in these seminars. Before one seminar, two researchers had visited the same teacher a few days apart; the second had the opportunity to see implemented the first's suggestion to incorporate proportional reasoning into a lesson. Describing this lesson sparked a discussion of teachable moments—awareness of situations in which opportunities to develop important ideas, in this case proportional reasoning, arise.

The one topic tested on the initial Content Knowledge Test but not addressed during Year 1 was that of weighted average in rate problems. This difficult topic was approached in Year 2 through the use of P. Thompson's *Over and Back* (1994) microworld.

Just as in Year 1, most of one seminar was devoted to discussion of students' fraction-understanding-test and interview results. The teachers appreciated the limitations of the pencil-and-paper instrument, even though it focused on conceptual learning and the greater richness of the responses in interviews in which answers could be probed for reasoning and in which misinterpretations of the problems were evident.

During these Year-2 seminars, even more than in the Year-l meetings, the teachers often raised questions or shared classroom experiences that led to extended discussions (e.g., Darota gave students a problem to do individually so that she could work on report cards, but the problem instead turned into an extended lesson on ratio). Issues about standardized tests and textbooks were raised repeatedly. The importance of the teachers' having deep understanding of the content, the big ideas within a topic, the connections among topics—instead of merely presenting interesting problems that are not necessarily part of a bigger, overall picture of rational

numbers—was recognized by the teachers and was raised by them more than once during the Year-2 seminars.

Year 2 concluded with a seminar in which we, the researchers, explained that we would now be trying to tell what had been learned from this project, and the teachers were asked to reflect on their participation and to tell what had been learned from their points of view. The teachers spoke quite passionately about how much they had learned and about the need for all teachers to have more opportunities to focus on mathematics during professional development.

Excerpt (a) from Swafford, J. O., Jones, G. A., Thornton, C. A., Stump, S. L., & Miller, D. R. (1999). The impact on instructional practice of a teacher change model. *Journal of Research and Development in Education, 32*(2), 69–82.

Excerpt (b) from Swafford, J. O.; Jones, G. A., & Thornton, C. A. (1997). Increased knowledge in geometry and instructional practice. *Journal for Research in Mathematics Education, 28*(4), 467-83.

(a)

Participants in the Intervention

The subjects were 48 middle-grades (4-8) teachers participating in Project LINCS. These participants, all volunteers, came from 30 schools and 12 school districts within a 50-mile radius of a Midwestern university. Pairs of participants from the same school were actively sought, but only 32 came from schools with 2 or more participants. Their mean number of years of teaching experience was 13.6.

Intervention Program

Project LINCS was a 3-year intervention program designed to enhance teachers' knowledge through annual 4-week summer content courses, accompanying 8-hour research seminars on student cognition, and 6 half-day seminars during the academic year focusing on pedagogical practice. The intervention also incorporated structured on-going teacher collaboration and reflection.

Content courses. The summer content courses addressed probability and statistics in year 1, geometry in year 2, and algebra in year 3. The probability and statistics course emphasized the exploration of data and the use of simulation to determine probabilities. Visual displays and descriptive statistics were used to examine characteristics and patterns in data; and theoretical probabilities, simulations, and data analysis were used to solve a wide variety of probability problems. The geometry course focused on the exploration of two- and three-dimensional shapes using the van Hiele (1959/1985) levels of recognition, analysis, and informal deduction as a basis for instruction. In particular, the course incorporated an investigation of polygons and their properties; tessellations; polyhedra and their properties; length, area, and volume measures; and motion geometry. The algebra course explored families of functions in problem contexts. This exploration used graphical, tabular, and symbolic representations to investigate linear, quadratic, and exponential functions. The instructional approach adopted in each course can be described as "teaching via problem solving" (Schroeder & Lester, 1989) and modeled the pedagogy advocated in the half-day seminars. Computers and graphics calculators were used in all courses.

Research seminars on student cognition. The companion research seminar reviewed and discussed research findings on students' cognition in each of the three content areas and reflected on the implications of these for classroom instruction. The seminars examined the research on the development of probabilistic thinking (Shaughnessy, 1992); van Hiele levels (Fuys, Geddes. & Tischler, 1988); and students' understanding of variables and their uses (Kieran & Chalouth, 1993). Each year, participants also interviewed a student at their grade level in order to evaluate the student's thinking with respect to that summer's content topic.

Seminars on pedagogical practice. During each of the 3 academic years, participants attended 6 half-day seminars. The seminars analyzed practices advocated in the *Teaching Standards* (NCTM, 1991). Topics included alternative assessment, cooperative groups, classroom discourse, worthwhile mathematical tasks, and writing in mathematics. These practices were discussed in the seminars, and suggestions for their implementation were presented.

Collaboration and reflection. Each seminar had a formal segment where participants shared ideas and successful practices as well as informal opportunities for sharing during breaks and activities. Also, as part of each district's contribution, participants were given a half-day per semester for collaboration within their building.

Each year participants videotaped and analyzed two classroom lessons. They also kept a reflective journal, and at the end of each year they provided a summary of their journals for project staff. This summary highlighted changes that had occurred in their teaching and identified their goals for the coming year. The final journal summary reflected on the entire 3 years and discussed how their instructional practice had been influenced by the project.

(b)

Subjects

The subjects were 49 middle-grade (4-8) teachers participating in Project LINCS, a 3-year professional development project funded by the National Science Foundation. The participants, all volunteers, were drawn from a commuting distance of a midwestern university and received 5 semester hours of graduate credit and a summer stipend for each year of participation. They were divided into two sections for the summer courses. Group 1 comprised the Grades 4-5 teachers and Group 2 the Grades 6-8 teachers.

Intervention Program

Each year of Project LINCS consisted of a 4-week summer session and six half-day seminars during the academic year. Each summer the program emphasized a different subject-matter content, with geometry being the focus area during the second summer. The geometry program consisted of a mathematics content course on geometry, which met 3 hours a day for 4 days a week, and a research seminar, which met for 2 hours once each week. The two sections of the content course were taught by two mathematics education faculty, one of whom was the second author. The research seminar was conducted by the first author. The third author coordinated the academic-year seminars.

The geometry course focused on the exploration of two- and three-dimensional shapes through recognition, analysis, and informal deduction, with greater emphasis on analysis and informal deduction. Instructors adopted an instructional approach that has been described as "teaching via problem solving" (Schroeder & Lester, 1989). Using this approach, each session commenced with the presentation of a problem that embodied key aspects of the topic. Participants worked on the problem in small groups and then shared their solutions in a class discussion. During the class discussion, solution strategies were refined, extension problems were formulated and solved, connections were identified, and discussions ensued on the van Hiele level of key tasks associated with the problem. The textbook for the course, *Geometry: An Investigative Approach* (O'Daffer & Clemens, 1992), was compatible with the "teaching via problem solving" approach. As part of the course, the participants also developed an instructional unit and accompanying assessment plan for their respective grade levels.

The research seminar presented the van Hiele theory of cognitive development and instruction in geometry. This was followed by an examination of the research on the van Hiele levels of

students (Burger & Shaughnessy, 1986; Fuys et al., 1988; Mayberry, 1983; Senk, 1989). Research on geometry text materials (Fuys et al., 1988; Whitman & Komenaka, 1990) and the results of national and state assessments in geometry were also reviewed. In addition to the research readings, teachers had the option of either interviewing a student at the grade level they teach or analyzing instructional activities in their textbooks by van Hiele levels. For the student interviews, 36 items developed by Mayberry (1981) for assessing the first three van Hiele levels were used. The textbook analysis used the methodology described in Fuys et al. (1988). Both activities were designed to help make the research real to the participants by linking the results and methodology either to one of their own students or to their own textbooks. The interviews also served to give the teachers greater insight into their students' thinking about geometry.