SySTEMically Improving Student Academic Achievement in Mathematics and Science

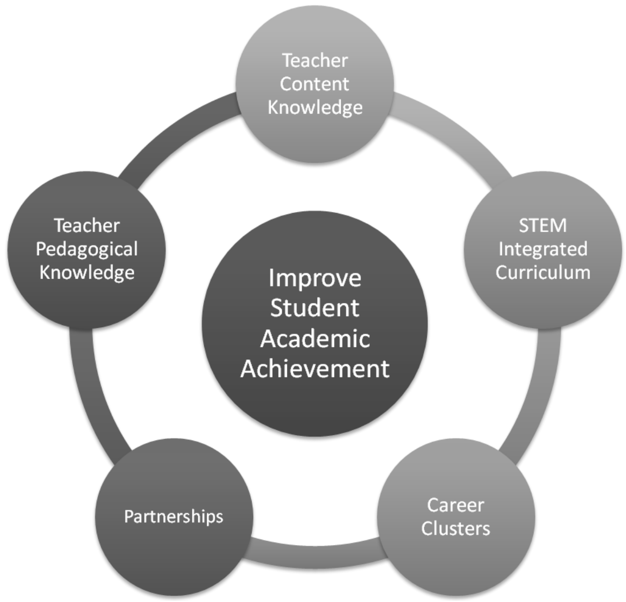
by Kevin Mason, Jerrilyn Brewer, Jerry Redman, Charles Bomar, Petre Ghenciu , Mike LeDocq and Carolyn Chapel

The need for high-quality professional development programs in mathematics and science has become increasingly important in the current climate of educational reform.[1] According to researchers Rolf K. Blank, Nina de las Alas and Carlise Smith, the success of standards-based reforms in education “requires teachers to have deep knowledge of their subject and the pedagogy that is most effective for teaching the subject.”[2] The Western Wisconsin Science, Technology, Engineering and Mathematics (STEM) Consortia Project—SySTEMically Improving Student Academic Achievement in Mathematics and Science—provided professional development for 60 K-12 teachers from nine different school districts in western Wisconsin. The project was funded by a Math and Science Partnership Grant from the Wisconsin Department of Public of Instruction.

The purpose of the Western Wisconsin STEM Consortia project (Figure 1) was to improve student academic achievement in mathematics and science by:

- Providing professional development in mathematics and science content knowledge.
- Providing professional development in evidence-based pedagogical practices.
- Developing integrated STEM curriculum projects related to career clusters.
- Aligning STEM curriculum projects with mathematics and science standards.
- Building strong, collaborative relationships among K-12, higher education and business partners.

Figure 1: Purpose of the Western Wisconsin STEM Consortia Project



The 2010 Summer STEM Academy focused on ecosystems and the interdependence of organisms (Wisconsin Model Academic Standards F.12.7 and F.12.8), scientific inquiry (Wisconsin Model Academic Standard C), and statistics and probability (Common Core Standards S-CP and S-MD). It also addressed effective pedagogical strategies in mathematics and science, including contextual teaching, problem-based learning, project-based learning and inquiry-based learning.

The teachers who participated in this professional development project included 20 elementary teachers (33.3%), 16 secondary math teachers (26.6%), 11 secondary science teachers (18.3%), 11 secondary career and technical education teachers (18.3%), one secondary math and science teacher (1.6%) and one special education teacher (1.6%). The sample of teachers was predominately female (66.6%) and Caucasian (100%), which reflects the teaching force in the state of Wisconsin. The ages varied, with 10 teachers aged 20-29 (16.6%), 16 teachers aged 30-39 (26.6%), 24 teachers aged 40-49 (40%) and 10 teachers aged 50 and above (16.6%).

Likewise, teaching experience varied, including two teachers with 0-2 years of experience (3.3%), eight teachers with 3-5 years (13.3%), 13 teachers with 6-10 years (21.6%), 26 teachers with 11-20 years (43.3%) and 11 teachers with 21 or more years (18.3%). Of the teachers, 22 had completed only a bachelor's degree (36.6%) and 38 had completed a master's degree (63.3%).

Data analysis revealed that of the 60 teacher participants, 83% demonstrated significant gains in mathematics content knowledge and 62% demonstrated significant gains in science content knowledge. This paper discusses the 2010 Summer STEM Academy and the development of the integrated STEM curriculum by K-12 teachers. Furthermore, this paper explains how this project is grounded in the *Baldrige Education Criteria for Performance Excellence*.[3] This may provide a useful guide for the design of future professional development endeavors in STEM education.

Literature review

This project was grounded in the belief that "teacher professional development is not an event, it's a process."[4] Teachers were provided time, experiences, resources and guidance to develop their knowledge of mathematics, science, curriculum and instruction. A study of professional development for teachers found that "most teachers considered time spent planning and learning with other teachers as most valuable" and that teachers "noted that this activity was vital to their growth and development as they worked to change their teaching practice."[5] Using a framework designed by the National Staff Development Council, this project involved three basic components of high-quality teacher professional development programs: context, content and process.[6]

The context or setting facilitated learning as a "communal activity" where participants could "interact, study together, discuss teaching and help one another put into practice new skills and strategies."[7] A sense of community and the "supportive coaching" that it provides is necessary not only to bring about changes in beliefs but to help teachers develop and maintain a sense of efficacy regarding new teaching strategies.[8]

The content of the professional development experience was designed to deepen teachers' knowledge of the subjects being taught, sharpen teaching skills, keep up with the developments in the field and contribute new knowledge to the profession.[9] The 2010 Summer Academy employed a learning for understanding framework that included four related forms of mental activity from which mathematical and scientific understanding emerges:[10]

1. Constructing relationships.
2. Extending and applying mathematical and scientific knowledge.
3. Justifying and explaining generalizations and procedures.
4. Developing a sense of identity related to taking responsibility for making sense of mathematical and scientific knowledge.

The process of professional development was based on sound educational practice that presents information and learning activities in familiar and useful contexts.[11] The Career Pathways Framework provided a real-world context that was useful for the development of the STEM-integrated curriculum projects.[12] According to expert Sandra Harwell, professional development also should support interaction among master teachers, take place over an extended period of time, and provide opportunities for teachers to try new behaviors in safe environments and receive feedback from peers.[13] This professional development project met each of these criteria.

2010 Summer STEM Academy

In the 2010 Summer STEM Academy, teachers were immersed in asking and investigating mathematics and science questions in the classroom, at outdoor locations and at a variety of business sites. Research has shown that "teachers, like students, best learn science and mathematics by doing science and mathematics, by investigating for themselves and building their own understanding."[14] Mathematics and science concepts and skills were taught and experienced by the teachers in the context of how math and science are applied by scientists, researchers, and others in business and industry.

At the same time, the teachers were given instruction in pedagogical strategies in mathematics and science and spent considerable time in groups—arranged by grade levels—to discuss how these concepts and experiences in math and science related to the K-12 curriculum and the students they teach. This led to the successful development of the integrated curriculum projects, which were taught in the K-12 classrooms the following school year.

Content knowledge in mathematics and science

The 2010 Summer STEM Academy focused on ecosystems and the interdependence of organisms (Wisconsin Model Academic Standards F.12.7 and F.12.8), scientific inquiry (Wisconsin Model Academic Standard C), and statistics and probability (Common Core Standards S-CP and S-MD). To address these standards, a number of activities were utilized. For example, the Karner Blue butterfly (*Lycaeides melissa samuelis*), a federally listed endangered species, was studied as a model organism.[15] This species is dependent on the wild lupine (*Lupinus perennis*) as a host plant and has a mutual relationship with two species of mound building ants.

This concept was discussed in the classroom and then further presented by a wildlife specialist in a field setting. Teachers garnered firsthand knowledge from the expert and then simulated the experience of monitoring this endangered butterfly. Teachers were able to identify the habitat limitations upon this species, and further applied them to their grade band projects.

Teachers also engaged in habitat assessment at a local vineyard, identifying the soil and water conditions necessary for wine grapes. Teachers were provided soil kits to analyze soil nutrients and were provided assays to test for soil texture (ribbon test) and particle size.[16] These tests allow teachers to explore a variety of soil types and hypothesize to the successfulness of each for producing wine grapes.

The instruction in mathematics focused on concepts in probability and statistics, including tree diagrams, independent events, conditional probability, mean, median, mode, range and standard deviation (Common Core Standards S-CP and S-MD). Rather than being introduced as separate topics, the probability and statistics concepts were introduced as a way to provide solutions to the questions that emerged from the participants' scientific inquiry activities.

All participants do not learn in the same manner, and projects that focused on specific learning objectives provided a modality for some to discover statistical concepts that may not have been grasped within the formal classroom setting. Other participants, while they grasped the concepts, expanded their understanding of statistical concepts through the use of projects. MS Excel was used to summarize the collected data, run the statistical analysis and present data in graphical form, including histograms and bar graphs. In addition to learning basic skills, the teachers learned how MS Excel can be used to investigate questions in a real-world context with K-12 students.

Pedagogical content knowledge in mathematics and science

Teachers received instruction and guidance in the use of effective pedagogical strategies in mathematics and science, including contextual teaching, problem-based learning, project-based learning and inquiry-based learning. The REACT model of contextual teaching emphasizes: relating, experiencing, applying, cooperating and transferring.[17]

Problem-based learning helps students to "build their knowledge and skills as they solve a real problem or answer an important question—not through abstract exercises."[18] Similarly, project-based learning often begins with a question or problem to solve. Project-based learning then engages students in designing and creating a "final product that addresses the driving question."[19] Inquiry-based learning provides students with the opportunity to "develop the ability to think and act in ways associated with inquiry."[20]

According to the National Science Education Standards, the process of scientific inquiry involves: asking questions, designing investigations, gathering data using scientific tools and techniques, analyzing and representing data, constructing explanations and conclusions, and communicating and defending findings.[21] These theories of learning were taught and modeled throughout the summer academy and later applied by the teachers in the development of the integrated curriculum projects.

Integrated curriculum projects

During the 2010 Summer Academy, the 60 teachers were divided into ten multidisciplinary grade band teams to develop an integrated STEM curriculum project. The grade-band teams included two K-2 teams, two 3-5 teams, three 6-8 teams and three 9-12 teams. Each of the projects addressed the mathematical topics of mean, median, mode and range, and the science topics of organisms, populations and ecosystems. The curriculum developed included an overview, scenario, learning objectives, alignment to standards, lesson plans, test blueprint and assessments for each project. Table 1 summarizes the ten integrated curriculum projects developed during the 2010 Summer Academy. The integrated curriculum projects are available online at http://www.uwstout.edu/wwsc/index.cfm.

Table 1: 2010 integrated curriculum projects

Grade band	Project title	Project purpose
K-2	Loopy for Ladybugs	To facilitate student understanding of living things and their environment.
K-2	Amazing Animals	To introduce students to characteristics and structures of living things and how living things interact with one another and their environment.
3-5	PONDering Ideas	To facilitate student understanding of characteristics and structures of living things, the processes of life, and how living things interact with one another and their environment.
3-5	Project Karner Blue	To foster curiosity and stewardship in students by establishing a butterfly garden, and to study, monitor and investigate ecosystems, life cycles and photosynthesis.
6-8	Aromatic Adventures	To provide opportunities for students to study the benefits of producing and processing an indoor herb garden.

6-8	The Amazing Forest Race	To provide opportunities for students to navigate, sustain and evaluate the value of a forest.
6-8	What's the Dirt on Organics?	To provide students with inquiry-based activities to compare and contrast conventional and organic farming in the areas of soils, plant growth and food product choices available to consumers.
9-12	Creating a Frisbee Golf Course	To identify and evaluate ecological consequences of designing, building and implementing a local Frisbee golf course.
9-12	Pew – Dumpster Diving for the Environment	To develop awareness and knowledge of the benefits of recycling as it pertains to high school students and their local environment.
9-12	Something for Nothing? Repurposing Food Grade Oil into Biodiesel	To investigate the economic feasibility and ecological impact of converting recycled food grade oil for practical uses within the community.

Evaluation

The overall evaluation of this project was based on Guskey's Five-Level Model for evaluating professional development.[22] The project selected numerous evaluation tools to collect qualitative and quantitative data to establish baselines, monitor progress, provide feedback, and determine overall program quality and effectiveness. Table 2 lists the steps in Guskey's Model, the data collection instruments used and a summary of the evaluation results.

Table 2: Guskey's model, instruments and summary of results

No.	**Guskey's model**	**Project evaluation method**	**Summary of results**
1.	Participant reaction	Critical incident questionnaire	Participants rated overall

		Reflective journals/notebooks	quality of professional development at 8.4 on a 10-point scale.
2.	Participant learning	DTAM test for math AIM test for science Contextual learning survey	83% (in math) and 62% (in science) of participants demonstrated significant gains at the 0.05 level.
3.	Organizational support and change	Partnership survey	13 out of 14 partnership members stated that partnership benefits exceed or greatly exceed drawbacks.
4.	Participant use of new knowledge and skills	STEM integrated project assessment rubric	Ten high quality integrated STEM projects were developed and shared.
5.	Student learning outcomes	WKCE assessments GIZMO computer simulations (year one) Benchmark assessments (year two)	At all four grade bands, there were significant differences at the 0.05 level when comparing post-tests results for the treatment and comparison groups.

DTAM = Diagnostic Teacher Assessment in Mathematics

AIM = Assessing the Impact of Math-Science Partnerships

WKCE = Wisconsin Knowledge Concepts Examination

Gizmo = an online repository of math and science simulations

Teacher evaluation

The principle investigator and external evaluator selected an overall pre-experimental design for teacher participant evaluation. A one-group pre-post-test method that involved three steps:

1. Administration of pre-test measuring the dependent variable.
2. Application of the experimental treatment.
3. Administration of post-test measuring the dependent variable again was used.

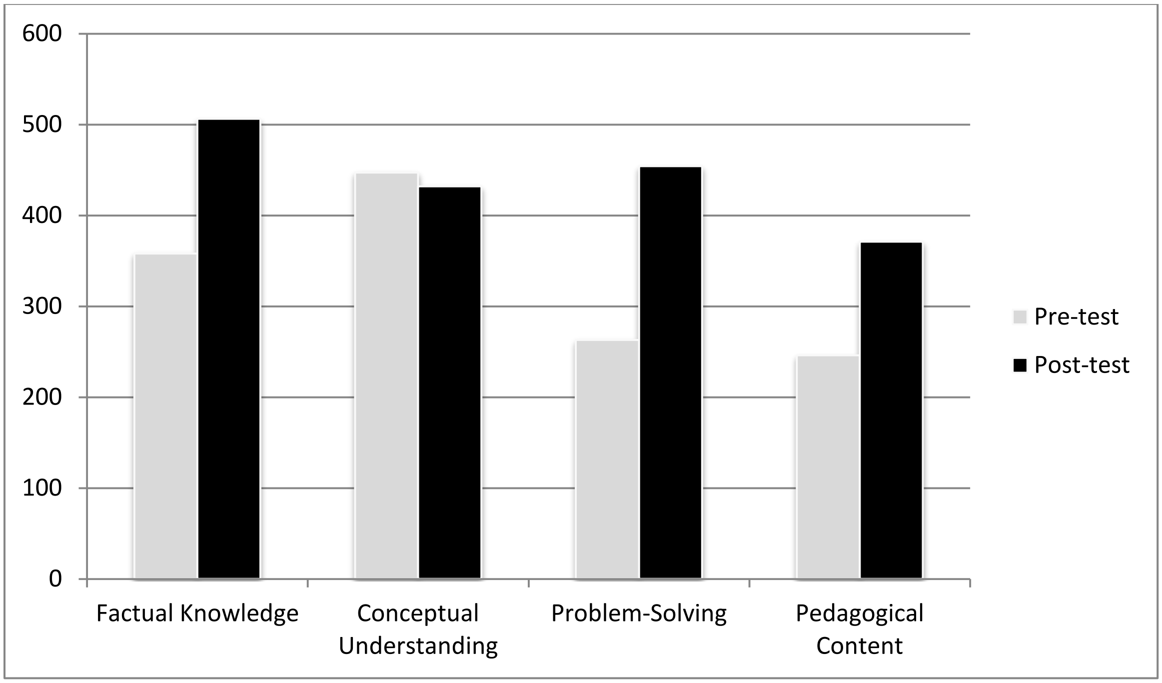
Use of this design (no control group) was justified because researchers were confident that extraneous factors could be estimated with a high degree of certainty or could be safely assumed to be non-existent. The dependent variable analyzed was teacher content knowledge in mathematics and science. The experimental treatment consisted of 100 hours of STEM professional development.

Sample size included 60 K-12 teachers who were administered two standardized instruments in a pre and post-test format: Diagnostic Teacher Assessment in Mathematics (DTAM): University of Louisville; Assessing the Impact of Math-Science Partnerships (AIM): K-8 Science Test (Horizon Research, Inc).

Data were analyzed by the test developers and the external evaluator. A one-tailed paired t-test was used to determine whether the difference between the pre and post-test scores and means were statistically significant. Data were disaggregated and analyzed to determine the effect of additional independent variables such as content, type of knowledge and grade level on math (Figure 2 and Table 3) and science (Figure 3 and Table 4) test scores.

Additionally, a contextual learning survey was used to measure teachers' pedagogical change and growth.

Figure 2: Type of knowledge comparison on DTAM math test



DTAM = Diagnostic Teacher Assessment in Mathematics

Table 3: Types of knowledge comparison on DTAM math test

Subcategory	Sample size	Significance level	T value	Pre-test	Post-test	Average difference
Factual knowledge	60	0.05	10.85*	Mean = 5.97 St dev = 1.87	Mean = 8.43 St dev = 1.25	Mean = ↑ 2.46 St dev = ↓ **0**.62

Conceptual understanding	60	0.05	-1.02	Mean = 7.45 St dev = 1.90	Mean = 7.2 St dev = 1.88	Mean = ↓ **0**.25 St dev = ↓ **0**.02
Problem-solving	60	0.05	15.31*	Mean = 4.38 St dev = 2.45	Mean = 7.57 St dev = 2.43	Mean = ↑ 3.19 St dev = ↓ **0**.02
Pedagogical content	60	0.05	6.24*	Mean = 4.08 St dev = 2.39	Mean = 6.18 St dev = 2.49	Mean = ↑ 2.1 St dev = ↑ 0.10

*Indicates significant differences

DTAM = Diagnostic Teacher Assessment in Mathematics

St dev = standard deviation

Figure 3: Knowledge comparison on AIM science test by grade level

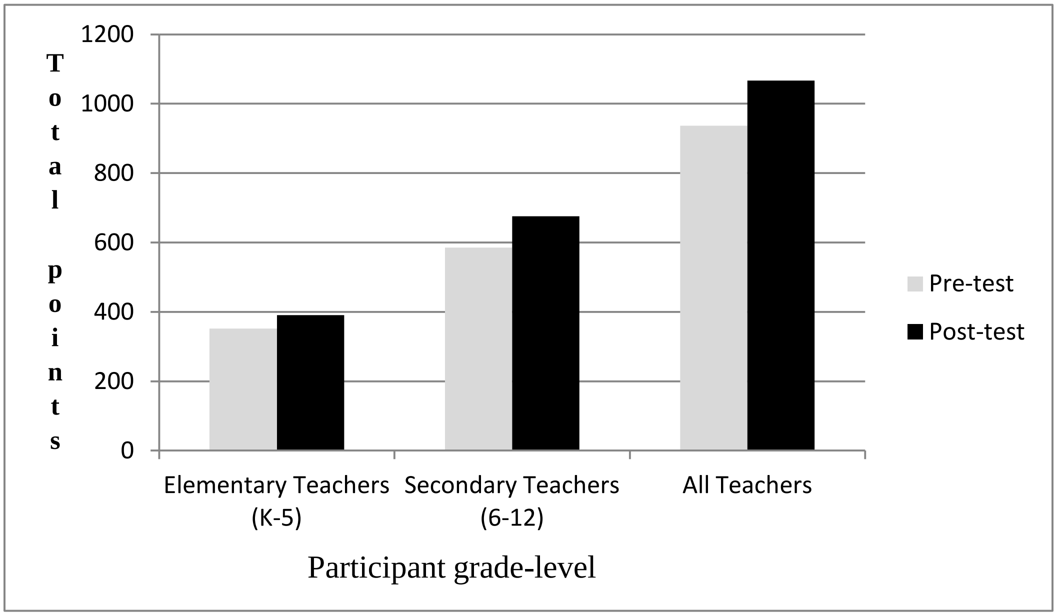


Table 4: Knowledge comparison on AIM science test by grade level

Subcategory	Sample size	Significance level	t value	Pre-test	Post-test	Average difference
Combined	60	0.05	2.698*	Mean = 15.61 St dev = 4.62	Mean = 17.78 St dev = 4.05	Mean = ↑ 2.17 St dev = ↓ 0.57
Elementary (K-5)	40	0.05	4.35*	Mean = 17.6 St dev =	Mean = 19.55 St dev =	Mean = ↑ 1.95

				0.96	0.79	St dev = ↓ 0.17
Secondary (6-12)	20	0.05	3.64*	Mean = 14.6 St dev = 0.71	Mean = 16.9 St dev = 0.64	Mean = ↑ 2.3 St dev = ↓ 0.07

*Indicates significant differences

There were four major successes identified in this project, based on the data collected:

1. 62% (37 out of 60 participants) demonstrated statistically significant gains in science content knowledge related to populations, ecosystems and interdependence as evidenced by pre and post-test scores on the AIM exam.
2. 83% (50 out of 60 participants) demonstrated statistically significant gains in mathematics content knowledge in probability and statistics as evidenced by pre and post-test scores on the DTAM exam.
3. Participants showed statistically significant gains in their understanding of contextual teaching and learning strategies on the teaching contextually survey.
4. On the summative assessment of the effectiveness of the two-week STEM Summer Academy, participants rated the overall quality of the professional development at 8.4 on a 10-point Likert scale. Some of our participants submitted quotes to describe the two-week academy, including: “smokin’ hot,” “fun with application,” “science Gizmos rock,” “awesome two weeks,” “STEM = Stimulating to Educators' Minds.”

Student evaluation

The principle investigator and external evaluator selected an experimental design for student evaluation. A non-equivalent control group method was used which includes such characteristics as: (1) identification of control and experimental groups; (2) use of pre-post-test format; (3) non-random assignment of subjects; (4) selection of matched-paired sets; (5)

analysis of trend data. The dependent variable analyzed will be student content knowledge in both mathematics and science.

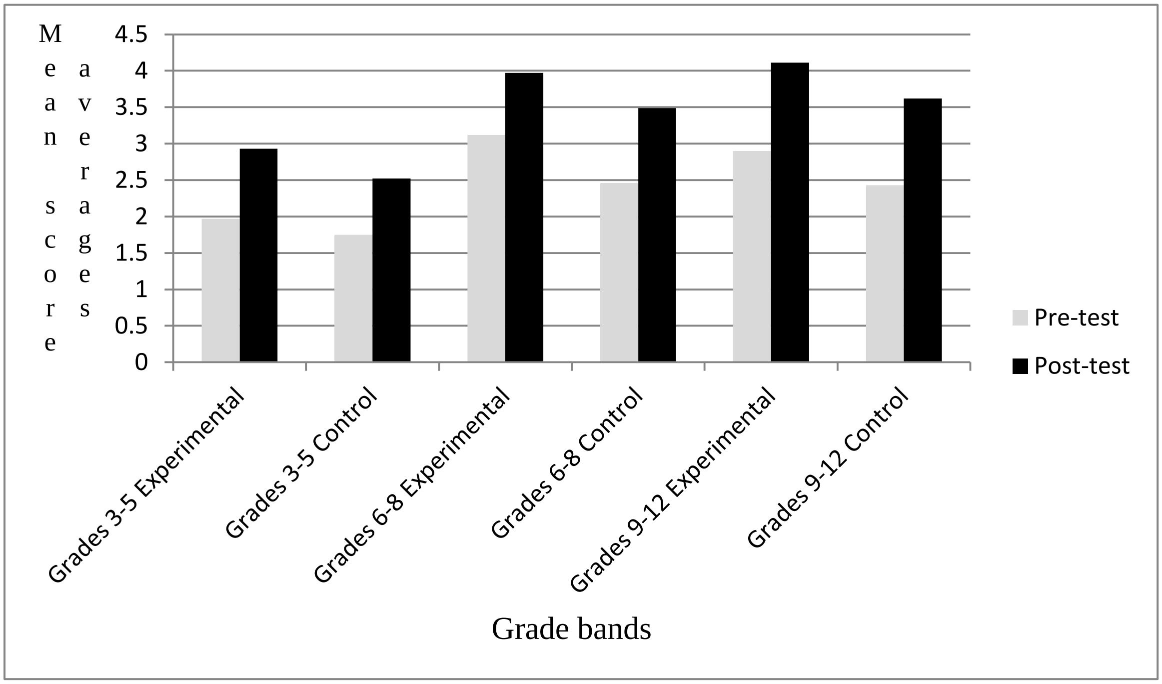
In the first year of grant implementation, student testing was somewhat limited. In the spring of 2011, teachers piloted the integrated STEM projects that were developed during the 2010 STEM Summer Academy. Teams at grades 3-5, 6-8 and 9-12 were to incorporate a lesson plan that included a Gizmo computer simulation and assessment into the project. Gizmo is an online repository of math and science simulations. Pre-K-2 teams needed to design their own assessment since the Gizmo program begins at grade three. At least one member from each team was required to implement the integrated STEM project, including teaching the math or science Gizmo lesson. The Gizmo assessment was administered in a pre and post-test format. Additionally, a control group was identified at each grade band for comparison purposes. Data were analyzed using descriptive statistics and t-tests to determine significant differences.

Results from the Gizmo simulations showed evidence of student achievement (Figure 4). At all four grade bands, the findings represented significant differences between the pre and post-test scores for both the experimental and control groups at the 0.05 level of significance. Furthermore, at all four grade bands, there were significant differences at the 0.05 level when comparing post-test results for the treatment and comparison groups.

Based on these results it appears that there was some effect on student achievement based on the professional development opportunity of the teachers; however, caution needs to be exercised when interpreting these results due to the small number of test items, lack of implementation fidelity and knowing what part of the increase is due to the integrated STEM project versus the Gizmo versus other instructional factors.

Additionally, findings from the 2010-2011 Wisconsin Knowledge and Concept Exams (WKCE) also indicated the 77% (844 out of 1057) students in mathematics and 76% (355 out of 466) in science who were enrolled in courses taught by grant participants were proficient or advanced on the annual Wisconsin assessment.

Figure 4: Gizmo student assessment results by grade level



In the future, the education faculty will work with each grade-band team to develop additional standards-based benchmark assessments for each integrated STEM project using commercially and teacher-developed pre and post-test items and tasks. This will strengthen the evidence of student learning in the remaining two years of the grant project. These assessments will include sample items based on a test blueprint using sound psychometric principles and established technical parameters. In the future, the principle investigator will administer pre-tests, teachers will teach the STEM lessons, and the principle investigator will administer post-tests.

The external evaluator will analyze the data using descriptive statistics, a one-tailed, paired t-test of significance. Valid and reliable results will be interpreted to measure science and math content learned. Additionally, student achievement will be monitored using Wisconsin's WKCE proficiency scores and adequate yearly progress measures. Assessment results will provide evidence to support the hypothesis that intensive, high-quality, integrated STEM professional development does improve student academic achievement in mathematics and science.

STEM Academy viewed as a Baldrige Process

The Western Wisconsin STEM Consortia Project—SySTEMically Improving Student Academic Achievement in Mathematics and Science—was conceptually grounded in the Baldrige Education Criteria for Performance Excellence.[23] The Baldrige interrelated core values and concepts provided the philosophical underpinning for project development and implementation.

Project developers engaged in visionary leadership by creating a "student-focused, learning-oriented model with clear and visible values and high expectations.[24] Learning-centered education that puts the "focus on learning and the real needs of students"[25] provided the framework for the professional development activities and the STEM Integrated Curriculum Projects that focus on students' active learning and developing problem-solving skills.

Valuing workforce members and partners was also central to developing the STEM approach. Project developers realized that "strategic partnerships or alliances are increasingly important kinds of external partnerships"[26] and that developing strong partnerships among K-12, higher education and the business community would serve to strengthen and expand long-term relationships. Integrating mathematical and science content knowledge and helping teachers understand how to apply these concepts in a real-world context was one aspect of this project design that supported partnership development. Another key aspect of the STEM project was its focus on the future and providing project participants with "training and practical applications of assessment methods and learning style information."[27]

Each STEM Integrated Project includes a variety of formative and summative assessment measures designed to assess student learning. Additionally, project success is measured by an increase in teacher content knowledge in mathematics and science, as well as by an increase in student academic achievement in both content areas. Most importantly, this project was developed using a systems perspective. Project developers chose a STEM focus because of its integrated approach to preparing students for STEM careers in the 21st century.

A basic tenet of this project is the belief that teachers need to improve their pedagogical and content knowledge to meet the needs of all students. Intentional selection of 60 K-12 teachers from nine different school districts was a commitment to building capacity for change and innovation in western Wisconsin. Our STEM Integrated Model (Figure 1) shows the inter-relationship among all parts of the project further demonstrating the systems approach that was fundamental in project design.

Conclusions

The STEM integrated approach has proven to be an effective professional development model that results in growth in teacher content and pedagogical knowledge—in both mathematics and science. Data analysis revealed that of the 60 teacher participants, 83% demonstrated significant gains in mathematics content knowledge and 62% demonstrated significant gains in science content knowledge. Aspects of the model that contributed to this effectiveness included: higher education faculty with subject-matter expertise; field-based learning activities; career pathway focus; two-week summer academy; multi-district collaboration; grade-band teams; and contextual, problem and project-based learning. Teachers embraced this integrated approach to professional development as evidenced by the wide range of STEM Integrated Projects they developed and taught in their own classrooms

The authors experienced both challenges and successes in the development and implementation of this professional development experience. The challenges included the limited amount of time available in the grant cycle, the development of assessment instruments, the inclusion of a wide variety of grade levels and disciplines, the logistics of facilitating field experiences for a large group, and establishing and maintaining partnerships with local businesses. The success of the project included the involvement of high quality faculty, effective communication and collaboration on the leadership team, the benefits of the field experiences, the use of technology and the overall design of the assessment.

The *Baldrige Education Criteria for Performance Excellence* provided a useful tool in guiding the design and implementation of this professional development project and contributed to the overall success of the project. The result was a professional development experience with visionary leadership, learner-centered activities, strong partnerships, a clear focus on the future and a systems approach.

The lessons learned from these challenges and successes can be applied to future professional development initiatives. Throughout the project, a plan-do-check-act cycle was used to make critical programmatic decisions both during and after the two-week summer academy. Intentional and frequent review of these data has provided opportunities to engage in continuous improvement and to make adjustments along the way vs. waiting until the project has ended. Replicating this project in other consortia or school districts will require a commitment to collaboration, communication and consistency as well as an understanding of a systems perspective.

In today's world of shrinking resources, it makes sense to use a collaborative, consortia approach for professional development, especially for small school districts that do not have the resources for a three-year, sustained project. Although approaches to professional development can vary widely, it is clear that an integrated STEM approach is an effective professional development model for improving teacher content and pedagogical knowledge in mathematics and science.

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