Middle School Math and Science Teachers Engaged in STEM and Literacy through Engineering Design (Evaluation)

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We describe a professional development program that supports integration of STEM and Literacy through Engineering Design for 24 in-service middle school math and science teachers in rural Appalachia. Through this program, teachers experience Engineering Design as learners, develop lesson plans utilizing engineering design to teach specific relevant math and science content standards and objectives, and receive formative feedback and content knowledge coaching as they implement, evaluate and refine those lessons.

Project TESAL (Teachers Engaged in Science And Literacy) is a three-year professional development program that includes annual two-week summer face-to-face intensive professional development opportunities and four additional day-long experiences throughout the school year. In addition, project personnel observe participants' classroom instruction, providing feedback and support on implementation of Engineering Design-focused lessons. In this paper, we describe the program and evaluation findings from the first two years of implementation.

Project TESAL successfully recruited a group of mathematics, science, and special educators, and engaged them in professional development they find valuable. The Teacher Efficacy and Attitudes toward STEM (T-STEM) survey revealed that professional development successfully increased participating teachers' confidence to teach engineering design, their confidence that they can influence their students' STEM performance, and their knowledge of STEM careers, as well as the amount they expect to utilize technology and instructional approaches aligned with STEM best educational practices.

Diagnostic Teacher Assessments in Mathematics and Science (DTAMS) for middle school showed that participating teachers initially did poorly outside of their content area focus. Closer inspection of items on mathematics and science assessments revealed difficulty with questions requiring understanding beyond simple procedural knowledge of the mathematics and areas of weakness in Real World Newtonian Physics (*MS-PS2-2* in Next Generation Science Standards) and Thermal Transport by Convection (*MS-PS3-3)*. We targeted these areas of weakness through a roller coaster design project as a concrete example of real world Newtonian Physics and a design project to manufacture a lunch box to keep food warm, as well as multiple applications of mathematical thinking to solve engineering design challenges.

Participating teachers improved their content knowledge in targeted areas and identified several strengths of Project TESAL. Participants particularly valued being active participants in learning, opportunities for collaborating with peers and outside experts around the work of teaching, focusing on subject matter content across mathematics and science and students' learning of that content, and the sustained ongoing nature of Project TESAL where the work teachers did in professional development was fully relevant to their work as classroom teachers. These strengths align directly with best practices for professional development and for overcoming the challenges of professional development specifically on math-science-engineering design integration and instruction.

Introduction

Common Core middle grades standards include engineering design in the science framework, but the design process is not easy to learn. Teacher preparation and scaffolding are key to implementation of design based learning and lead to significant student learning gains [1]. Project TESAL addressed teachers' knowledge of content and knowledge of pedagogy [2]. Teachers need deep understanding of the mathematics and science they will teach. They also need knowledge of how students develop understanding of content, how to set significant learning goals, how to select and implement appropriate instructional tasks, and how to assess learning [3]. Well-designed professional development experiences are integral to developing such knowledge and skills [4].

National standards documents make it clear that mathematics is an essential tool for scientific inquiry, and science is a critical context for developing mathematics competence [5-6]. Mutually reinforcing science and mathematics understandings while teaching either discipline is a pragmatic and readily available interdisciplinary opportunity [7-8]. *A Framework for Science Education* [9] gives engineering and technology a greater focus. In our approach, the *Common Core State Standards for Mathematics* [10] content domains (e.g., ratios and proportional relationships, statistics and probability) and standards for mathematical practice (e.g., making sense of and persevering in solving mathematical problems, modeling mathematics, choosing appropriate tools) are integrated with science and engineering practices from the next generation standards such as "asking questions and defining problems" and "using mathematics and computational thinking", as well as crosscutting concepts focused on "systems and system models" [11]. Engineering design projects provide extensive opportunities to engage in practices common to both the *CSSM* and *Framework*: defining problems, constructing explanations, developing models, using appropriate tools and attending to precision.

Engineering design done well requires an unfamiliar role for many teachers. Teachers must shift from evaluative to interpretive perspectives while moving away from guiding students to correct answers and toward emphasizing exploration and engagement [12]. Teaching practices must foster student reflection on their own reasoning and interpretation of problems [13]. Rather than warning students when they take a wrong step, teachers must use student errors as opportunities to focus on interpreting specific ideas and connections to the problem at hand [14]. For many teachers, this requires different work from that which they have likely experienced before as professionals and as learners. They must move away from transmission models of teaching and, rather, focus more on creating opportunities for students to explore, make sense of ideas, and support them in making connections.

Project TESAL targets development of these new roles for teachers as well as improved mathematics and science content integrated in an engineering design based method [12]. We strive to shift students and teachers from being processors of information toward becoming creators of mathematics and science models [13] as tools to help solve societally relevant scientific challenges through the design and development of appropriate technologies.

Program design and implementation

Project TESAL is a three year program including two weeks professional development each summer, two days each semester, and classroom observations/support (see Figure 1). Each year

is themed around science and literacy foci (Year 1: Physical Science / Argumentation; Year 2: Life Science / Informational; Year 3: Earth Science / Narrative) with grade appropriate mathematics. Participating teachers remain in the program all three years and are responsible for creating, implementing, and refining two lesson plans per year.

Figure 1: Project TESAL Program Design and Participating Teachers Building Roller Coaster

A brief example of our approach: Teachers experienced an engineering design lesson as learners in groups designing and building a paper roller coaster where a marble took 45 seconds to traverse the track. We introduced the design process (see Figure 2) and emphasized redesign in this context. Redesign led to a literacy assignment to write an instruction manual on how to build the redesigned coaster. Groups had to build each other's coaster from that instruction manual. Conversations during the coaster project, content knowledge tests, and later classroom observations highlighted specific content knowledge gaps for teachers, such as understanding how gravity, mass, and speed interact. We developed new engineering design lessons for teachers to engage in during professional development sessions to simultaneously model engineering design and strengthen teachers' content knowledge related to the highlighted gap areas.

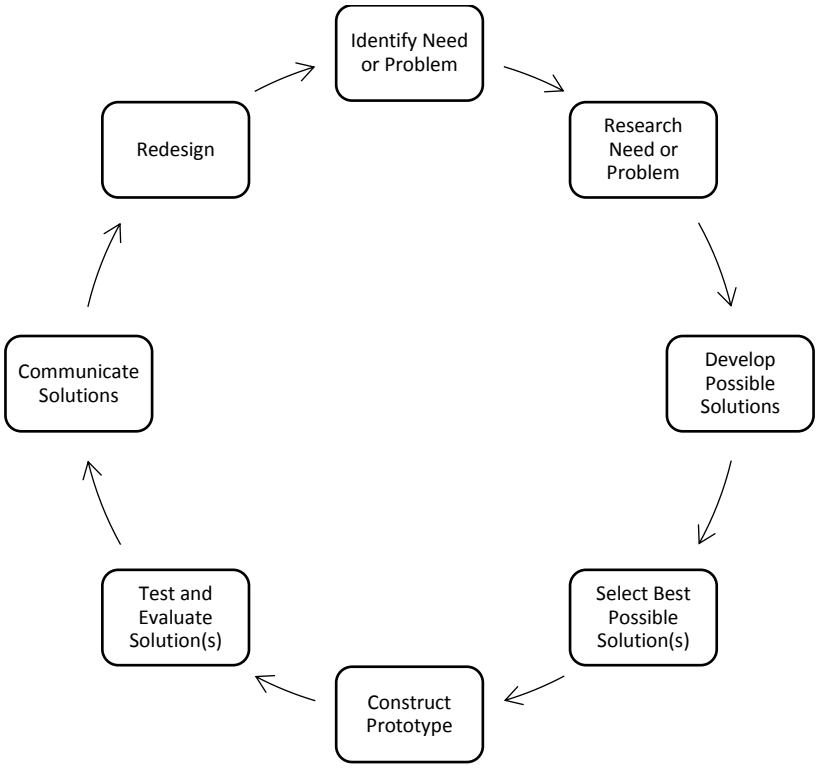

Figure 2: Design Process Model Utilized with Participating Teachers

Data Collection

We focus this evaluation on analysis of surveys (T-STEM), content knowledge tests (DTAMS), and focus groups each completed both before and after professional development, as well as teacher-generated engineering design lesson plans and observations as teachers implemented lessons in their classrooms.

The Teacher Efficacy and Attitudes Toward STEM (T-STEM) [15] Survey is intended to measure changes in teachers' confidence and self-efficacy in STEM subject content and teaching, use of technology in the classroom, 21st century learning skills, leadership attitudes, and STEM career awareness. The 63 items across 7 subscales utilize a 5 point Likert-type response format where higher numbers indicate more positive attitudes or higher self-efficacy in the construct being assessed (see Table 1). Strong reliability and validity has been reported for representative samples of mathematics and science teachers.

The Diagnostic Mathematics and Science Assessments for Middle School Teachers (DTAMS) [16] serve two purposes: (1) to describe the breadth and depth of mathematics and science content knowledge so that researchers and evaluators can determine teacher knowledge growth over time, the effects of particular experiences (courses, professional development) on teachers' knowledge, or relationships among teacher content knowledge, teaching practice, and student performance and (2) to describe middle school teachers' strengths and weaknesses in mathematics and science knowledge so that teachers can make appropriate decisions with regard to courses or further professional development. The assessments utilize a combination of

multiple choice and open response explanation format items to measure mathematics knowledge in four content domains (Number/Computation, Geometry/Measurement, Probability/Statistics, Algebraic Ideas) and science knowledge in three domains (Physical Science, Life Science, Earth/Space Science). A score of 20 indicates all items correct on each assessment. Strong reliability and validity data has been reported for these assessments.

Table 1: T- STEM subscales and representative items

Subscale	Sample Item
Eng. Design Teaching Efficacy/Beliefs (11 items)	I know the steps necessary to teach engineering design effectively.
STEM Outcome Expectancy (9 items)	When a student does better than usual in STEM, it is often because the teacher exerted a little extra effort.
Student Technology Use (8 items)	During STEM instructional meetings (e.g. science class, mathematics class, STEM-related clubs or organizations, etc.), how often do your students…Use a variety of technologies, e.g. productivity, data visualization, research, and communication tools.
STEM Instruction (14 items)	During STEM instructional meetings (e.g. science class, mathematics class, STEM-related clubs or organizations, etc.), how often do your students…Develop problem-solving skills through investigations (e.g. scientific, design or theoretical investigations).
21st Century Learning (11 items)	I think it is important that students have learning opportunities to…Lead others to accomplish a goal.
Teacher Leadership Attitudes (6 items)	I think it is important that teachers …Take responsibility for all students' learning.
STEM Career Awareness (4 items)	I know…About current STEM careers.

Project TESAL involves teachers from four rural counties with from 41% to 67% low-income students, less than 80% highly qualified teachers in mathematics or science, and below average mathematics and science standardized test scores in a state well below the national average. Five middle schools are designated by the state as "focus schools" with mathematics or reading achievement gaps in special education and low-SES subgroups. The 24 participating teachers

had 1 to 32 years teaching experience (median = 8 years) and considered themselves science educators (n=11), mathematics educators (n=8), special educators teaching math or science (n=4), or technology educators teaching math or science (n=1). All participants had at least a bachelor degree and 17 (70%) were highly qualified based on federal definitions.

Table 2: T- STEM pre-post means, standard deviations (SD) and paired samples t-test results.

N=22	Pre-PD Mean (SD)	Post PD Mean (SD)	Sig. (2-tailed)	Cohen's d
Eng. Design Teaching Efficacy/Beliefs	2.86 (.67)	3.86 (.41)	<0.01	1.49
STEM Career Awareness	3.38 (.78)	4.32 (.11)	<0.01	1.21
STEM Instruction	2.99 (.59)	3.41 (.64)	<0.01	.71
Student Technology Use	2.72 (.60)	3.09 (.91)	0.04	.62
Teacher Leadership Attitudes	4.53 (.37)	4.67 (.37)	0.21	.38
STEM Teaching Outcome Expectancy	3.41 (.41)	3.54 (.55)	0.15	.32
21st Century Learning Attitudes	4.58 (.36)	4.48 (.45)	0.37	.28

Table 3: Science and mathematics content knowledge means (standard deviations).

	DTAMS Science Content Score*	DTAMS Math Content Score*
Science Teachers n=11	16.18 (4.24)	13.09 (3.73)
Mathematics Teachers n=8	11.38 (3.96)	17.50 (2.88)
Special Education and Technology Teachers n=5	11.20 (4.94)	12.20 (3.70)
Total N=24	13.54 (4.72)	14.38 (4.02)

*Note: DTAMS Science and Math score out of 20 total possible on each measure.

Summary findings and discussion

The Teacher Efficacy and Attitudes toward STEM (T-STEM) survey[15] revealed large significant ($p<.05$) increases in Engineering Design Teaching Efficacy/Beliefs and STEM Career Awareness, as well as medium-sized significant increases in Student Technology Use and STEM Instruction (Tables 1 and 2). Diagnostic Teacher Assessments in Mathematics and Science (DTAMS) [16] showed science teachers outperformed their peers in science as did mathematics teachers in mathematics (Table 3). Special education and technology teachers struggled with both assessments. Mathematics item analysis revealed incorrect responses distributed across mathematical topic (e.g., data analysis, expressions and equations, rational number, proportional reasoning). While teachers did well applying an algorithm or formula, they struggled with questions requiring analysis, reasoning, and application. Science item analysis revealed two areas of weakness described here in the context of Next Generation Science Standards[11].

1) Real World Newtonian Physics (*MS-PS2-2= Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object.*) In particular one half of the teachers were not able to correctly identify the relative motion of an object dropped from a plane or articulate how to consider friction forces.
2) Thermal Transport by Convection (*MS-PS3-3= Apply scientific principles to design, construct, and test a device that either minimizes or maximizes thermal energy transfer.*) In particular only 7/24 teachers correctly identified that wall insulation traps pockets of air that prevent heat to flow by convection.

We targeted these areas first summer through the roller coaster design project and a design project to manufacture a lunch box to keep food warm. After classroom observations revealed more specific misconceptions, we developed new engineering design lessons to address those misconceptions.

Participating teachers developed and implemented with students in their classrooms at least two engineering design lessons per year. All lessons must address grade appropriate engineering design, literacy, and mathematics or science (many address both) content standards. One example, the Gingerbread House, engineering design lesson handout is provided in Figure 3, and the rubric for assessing students' learning in that lesson is Figure 4. Engineering design lesson plans developed by participating teachers during year 1 covered the following topics:

- Design a Roller Coaster (3 science educators, 2 math educators, 2 special educators: 4 schools),
- Design process to make the perfect hard-boiled egg (1 science educator, 1 special educator: 2 schools)
- Design an ice cream cone business (1 math educator)
- Design a healthy meal plan from McDonalds (1 technology educator)
- Design a tall and safe gingerbread house (1 math educator; see figure 4 below)
- Design a skating ramp (1 math educator)
- Design a shoe box that can be made from a single piece of cardboard (1 special educator)

- Design a scalable process to make a non-Newtonian fluid Oobleck (1 math educator, 1 science educator: same school)
- Use the design process to select a cell phone provider for a medium sized company (1 math educator)
- Design an air-bag (1 science educator)

Observations were conducted in classrooms during implementation of Project TESAL lessons. As an example, one theme that emerged across classroom observations and focus groups was that teachers almost uniformly noted that design based instruction dramatically increased engagement of special education students. One special education teacher in a low performing school first facilitated a design project to make a perfect hard-boiled egg. "*Students went home and asked their parents and grandparents to teach them to boil an egg and practiced with them. They then sat in the classroom carefully watching the water boil timing every step. I had never seen that level of engagement with this group of students. It has made me a believer*". The same teacher developed a second lesson to design a shoebox from a single piece of cardboard. Students designed prototypes and made a final scale model. Two special education students who have had limited success in the classroom designed an innovative triangular prism design – "*whenever they are struggling in class now I remind them of their success on the shoe box project. I am working on design projects to use in the Spring Semester with them now*."

Discussion

Project TESAL successfully recruited a diverse group of mathematics, science, and special educators, and is engaging them in professional development they find valuable. Project TESAL increased participating teachers' confidence to teach engineering design and their knowledge of STEM careers, as well as the amount they utilized STEM educational practices that are effective for their students. Participants valued being active participants in learning, opportunities for collaborating with peers and outside experts around the work of teaching, focusing on content across subjects and students' learning of that content, and the sustained ongoing nature of support and feedback through Project TESAL. These strengths align with best practices for professional development especially on math-science integration and engineering design [4-8, 17-20].

A key strength of Project TESAL is that the collaborative project team involves WV Regional Education Service Area personnel who have authentic long-standing relationships with key schools and teachers in the area working closely with university faculty who have deep engineering, science, and mathematics content knowledge as well as education pedagogy, curriculum resource, literacy, and educational evaluation/research expertise. The fact that the project team brings together individuals with expertise in a wide variety of areas, all relevant to the success of the project, provides opportunity to model the benefits of cross-disciplinary collaboration. Each individual has the opportunity to draw on her expertise to contribute to the work toward project goals and also gain knew understandings from working with others. This sort of team is quite unusual in the mostly rural Appalachian area where we work.

Part of the Project TESAL vision is recognition that the engineering design process applies authentically to design and redesign of professional development, design and redesign of teachers' instruction, and to engineering design projects for students. Through all these applications of engineering design, productive struggle, evaluation, and redesign in the context

of societally relevant scientific challenges are critical components that facilitate continuous quality improvement. The project team strives to both explicitly model and scaffold this mindset for and with participating teachers.

We recognize on-going opportunities for Project TESAL to overcome specific challenges. Valid and reliable assessment of teacher content knowledge coupled with available content expertise of project personnel is a strength. This strength gives rise to a challenge in determining how to address and appropriately scaffold the content needs of the prospective groups. In other words, how much do mathematics teachers need to know about science and how much do science teachers need to know about mathematics in order for them to meaningfully plan integrated instruction? In the context of somewhat low content knowledge scores and specific content deficiencies, especially outside of teachers' primary content area, how do we address content needs in safe and authentic ways? Some participating teachers commented on their appreciation of content outside their area of expertise. However, it is likely some participating teachers are uncomfortable opening their content knowledge gaps to remediation. We are developing an approach modeled on (sports) coaching with individualized specific skills focused training as a way to address this challenge within the context of teachers experiencing engineering design as learners. The main conception is that individualized assessment of content knowledge profiles across mathematics, science, literacy, engineering design, and educational pedagogy can be developed and utilized to target knowledge and skills development at individual, content area group, and whole group levels. We believe that content knowledge tests and classroom observation data, along with relationships built and strengthened through sustained engagement of teachers in engineering design teaching and learning, will allow us to realize the potential in this approach.

Gingerbread House Design

Task: Your task is to design and build a gingerbread house that has a solid structure and creative design using specific criteria.

Day 1: Design a gingerbread house on paper that meets the following criteria:

- Minimum area of 15 square inches
- Solid structure
- Functional roof
- One entrance
- Tallest house on Gumdrop Ave.

Day 2: Build the gingerbread house that your group designed using the materials available to you. Be creative!

Gingerbread House Fact Sheet

Height: _____

Area of the base: _____

Surface area: _____

Day 3: Structure Assessment

According to meteorologists, on Thursday, December 17, 2015, Gumdrop Avenue will experience blizzard like conditions accompanied by a magnitude 4 earthquake.

Day 4: Re-design

Does your gingerbread house need re-designed? Below, design a plan for improving your original design. How will you improve the structure of your existing gingerbread house?

Figure 3: Gingerbread House Design lesson

Gingerbread House Design Project Rubric				
40 points possible	Professional Engineer 10 points	Apprentice 6-9 points	Engineer in Training 2-5 points	Needs additional Training 1 point
Structure	House has a sturdy structure, entrance and functional roof and a clear design	House has a sturdy structure and a clear design	House stands, but has a sloppy design	House does not stand and candy has no order
Creativity	House shows personality and creativity with a clear design	House shows personality and creativity	House shows some personality and creativity	House is lacking personality and creativity with poor design
Collaborative Effort	Outstanding collaboration with peers and respectful behavior	Moderate collaboration with peers and respectful behavior	Very little collaboration and respect	Lacks collaboration and respect
Participation	Maintained focus on the task, shows attention to detail, has a positive attitude and assists peers	Maintained focus on the task and has a positive attitude	Very little focus on the task and moderate effort	Not focused on the task, complaining and no effort. Eating candy

Figure 4: Gingerbread House Design rubric

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