Developing Engineering Content for K-12 STEM Classrooms by Providing a Hands-On Engineering Design Experience for Teachers: A Case Study

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Introduction

The integration of engineering content in K-12 math and science subjects has been a growing phenomenon¹. Because of the strong connections that can be established between engineering, math and science, several studies have been conducted and have reported on the positive implications of engineering education in K-12 classroom settings². Such benefits include: (i) an increased student motivation to learn math and science concepts^{3, 4}, (ii) an increased student learning and achievements in math and science⁵, and (iii) an increased interest in pursuing a career in the science, technology, engineering and math (STEM) field⁵. There have been several proposed strategies for infusing engineering content in K-12 math and science subjects. These strategies could be cast into two categories. In the first category, engineering is introduced to K-12 classrooms as a unique discipline and engineering contents are often offered as pre-packages courses, often without the involvement of teachers in the engineering content development phase^{6, 7}. In the second category, engineering content is embedded in required math and science subjects⁸. Both approaches have their merits. While there is an ongoing effort in the nation to increase K-12 math and science teachers' content knowledge, it is important to recognize that teachers can potentially become more confident to teach challenging concepts and know how to relate them to real-world engineering applications if they participate in a professional development program that gives them the opportunity to experience engineering.

In its efforts to bring engineering into K-12 classrooms, the University of Texas-Pan American (UTPA) has partnered with several school districts in the region. The main objectives of this partnership are: (i) providing an engineering research experience for K-12 math and science teachers, and (ii) helping teachers translate the gained experience into relevant hands-on engineering activities for their classrooms. The offered professional development program combines the following activities:

- K-12 Teachers are recruited for a summer program held at UTPA where they conduct engineering research under the mentorship of engineering faculty.
- Teachers and the professional development personnel collaborate on developing develop engineering learning activities for the teacher participants' classrooms.
- Professional development personnel visit teachers' classrooms to observe the implementation of the new engineering learning activities and to provide feedback to teachers.

The professional development program provides an opportunity for teachers to be more knowledgeable about engineering and to become better equipped to teach engineering in their classrooms. Because teachers experience engineering, they are more likely to feel confident bringing engineering into their classrooms.

There is a number of papers that discuss the involvements of K-12 teachers in engineering research⁹⁻¹¹. However, there is a limited amount of research that examines the challenges and best practices for collaborating with teachers to develop engineering content for K-12 math and science classrooms. The goal of this paper is to describe factors that must be considered when engaging teachers to develop and implement engineering content for K-12 classrooms. The research questions that guided the study presented in this paper are as follows:

- (1) What are the main considerations for engaging math and science teachers in engineering research and design?
- (2) What are the challenges that teachers face and what of type of support should be provided to help teachers translate their engineering research into engineering content relevant to the math and science concepts they teach.

This paper presents the methods and results of a case study where a team of three teachers were engaged in engineering research that consisted of building an experimental setup to study the feasibility of using electrospun carbon nanofibers as the basis for a glucose biosensor. The paper provides an overview of the research project conducted by the teachers and describes the challenges of translating the engineering research experience into engineering curriculum content for the teachers' classrooms. The results of the engineering curriculum contents developed through this program and the observations of their implementations in teachers' classrooms during the academic year are reported and discussed.

Hands-On Engineering Design Experience for Teachers

The professional development program at UTPA engages middle and high school math and science teachers in engineering research activities that are conducted over a six week period during the summer. During each cycle of the program, four different engineering research projects are offered and recruited teachers are grouped into four teams of three. The teams are formed based on several considerations that include: (i) teacher's interest in the engineering research topic, (ii) K-12 math or science subject and grade level taught by the teacher, and (iii) teacher's background. The summer program offers several professional development seminars and technical workshops to provide the necessary tools and knowledge for teachers to conduct the assigned research projects and to help guide them to translate their research experiences into relevant educational hands-on activities they can implement in their classrooms during the academic year. This paper presents the research activities conducted by one team of teachers who, under the mentorship of engineering faculty, worked on designing an experimental set up to study the effectiveness of using electrospun carbon nanofibers (ECNFs) to detect glucose level.

None of the teachers on the nanotechnology team had a previous background in nanotechnology and none of them had worked on an engineering research project prior to joining this professional development program. Hence, strategic steps had to be taken to ensure that teachers are effectively introduced to the research topic and are kept from feeling overwhelmed by the expected challenges of the proposed engineering research project. Teachers spent the first two weeks of the summer program reading background materials and working with the faculty mentors to formulate the research problem. A hands-on workshop was offered by the library staff

to show teachers how to conduct electronic searches of technical articles. During the literature review phase, teachers learned about biosensors and their applications. They learned that biosensors are sensors used to analyze biomaterial samples by converting a biological response into an electrical signal. They learned that biosensors are used in various applications such as the development of pharmaceutical drugs, environmental field monitoring, scientific crime detection, quality control of food products and other medical applications. The first phase of the literature review provided the main context of the engineering design project. Further readings on the subject allowed teachers to learn that bienzymatic glucose biosensors that use vertically aligned carbon nanofibers (VACNFs) were shown to detect glucose¹². Teachers also learned that manufacturing VACNFs is an expensive process. This phase helped to clarify the goal of the proposed research project that consisted of determining whether non-aligned electrospun carbon nanofibers (ECNFs) could be used as the basis for a biosensor to detect glucose, hence providing a potential cheaper alternative to VACNF-based glucose biosensors.

To investigate whether ECNF can successfully detect glucose, teachers built an experimental setup to study the voltage-current characteristics of ECNF both dry and mixed in various bienzymatic solutions. The results of the experimental investigations showed that when ECNF is added to an aqueous bienzyme solution, it can positively detect glucose concentrations as low as 2.0mM (2.0 millimole per liter). The study has demonstrated that ECNF has the potential of being used as the basis for a glucose biosensor, hence providing a potential cheaper alternative to existing glucometers used by diabetics to manage their disease. At the conclusion of the summer program, the teacher team prepared a research poster that was presented to other teachers, students, faculty, and school administrators at the professional development program summer symposium held at the University.

The teachers found the engineering research project to be interesting, engaging, and rewarding because of its tangible applications and its potential benefits to humankind. In fact, in the United States diabetes affects 25.8 million people (over 8% of the population), including an estimated 7 millions of undiagnosed diabetics¹³. Diabetes is the seventh leading cause of death in the United States. It is also the leading cause of kidney failure, blindness, lower-limb amputations and a major cause of strokes and heart disease¹³. Because this research project has tangible real-world applications, teachers felt confident that they could easily communicate aspects of their engineering research experiences to their students and provide concrete examples of what engineers do.

Developing Engineering-Based Lesson Plans

In addition to teachers' participation in the engineering research project, an important component of the professional development program is to *translate* the gained engineering research experience into hands-on learning activities for the math and science classrooms. Before the teachers started the summer program, it had not been determined which existing lesson plans should be redesigned to incorporate engineering-inspired learning activities. However, during the initial curriculum development meetings, teachers were asked to identify some important math and science concepts that their students either find difficult to understand or show no interest in learning. Also, it was made clear to teachers that translating the engineering research experience into hands-on educational activities for their classrooms does not mean that those

activities should be developed as scaled down versions of the research projects. It is worth noting that before the start of the program most of the recruited teachers incorrectly interpreted the curriculum development requirement as simplified versions of the engineering research projects they were assigned to work on during the summer period.

As teachers progressed in their research, they were asked to identify one or two important elements from their research experiences that could be linked to the concepts they teach in their classrooms. The idea was to relate the math and science concepts they teach to real-world engineering applications and potentially use their engineering research experience as a motivation and/or background context for the hands-on educational activities they were required to develop as part of their participation in the professional development program. To facilitate the curriculum development process, weekly lesson development sessions were held with a curriculum and instruction specialist to guide the teachers in the development of the hands-on educational activities.

The following elements of the research project were identified as relevant to the subjects taught by the teachers: (i) sensors, (ii) data analysis, and (iii) design constraints. These elements were found to be translatable to relevant educational activities that teachers would be able to implement in their classrooms. During the weekly curriculum discussions, teachers discussed their research experiences and shared ideas for their learning activities with other program participants and the program management team. Throughout the lesson plan development sessions, inputs from teachers, engineering and education faculty were instrumental in formulating the engineering-based learning activities.

To serve as a motivation for students' learning, each activity is expected to have an engineering connection that shows how engineers apply math and science concepts to design new systems and/or to solve engineering problems. As teachers became more knowledgeable about the biosensor research project, they were able to improve the formulation of the engineering connections to their lessons. In addition to the engineering connection, each learning activity was expected to include a classroom challenge intended to have students either solve an engineering problem or collect and analyze data the same way engineers do.

Using the identified engineering research elements stated above, the following three engineering-based learning activities were developed.

Learning Activity 1 (Grade Level: 8 , Subjects: Algebra and Data Analysis):

The learning objectives of this activity are:

- To collect and organize data
- To create and analyze a scatterplot by determining the relationship between axis variables and data trend
- To draw line of best fit and make predictions

This activity relates math concepts to engineering. In this activity, students are introduced to several types of common medical sensor devices such as ear thermometers, forehead thermometers, glucometers and wrist blood pressure monitors. They use wrist blood pressure

monitors to measure their blood pressure and pulse. They also measure their heights and weigh themselves in order to calculate their Body Mass Index (BMI). Then, they use the collected data to create and analyze scatterplots of the various variables to determine if any relationships exist between the measured variables. Discussions about the negative or positive trends observed and possible health concerns conclude the activity.

While this activity does not involve an engineering design, the following engineering connection is presented to students: “Sensor devices are tools designed by biomedical engineers, and there are a variety of these sensors used in several applications including the medical field. Engineering research and development is continuing as engineers work to develop newer and better performing sensors. As part of the design cycle, engineers often need to measure, collect and analyze data. When investigating relationships between two variables, scatterplots can be utilized to enable engineers to examine any trends that may exist.”

Learning Activity 2 (Grade Level:8 , Subject: Science and Technology)

The learning objectives of this activity are:

- To build a pressure sensor using basic knowledge of electric circuits
- To understand the difference between pressure and force
- To measure, collect and graph sensor voltage readings as a function of time
- To identify linear relationships and compute rates of changes from voltage vs. time graphs

This activity involves a partial engineering design. In this activity, students construct a pressure sensor using a piece of conductive foam placed between two small copper plates that are connected to a battery source. Students apply pressure to the sensor by pressing on the copper plates using their thumb and index fingers. Using voltage probes, students then measure voltage readings that represent amounts of force being applied to the sensor. The collected voltage data is graphed as a function of time. Students use the graphed data to identify linear relationships and calculate rates of change.

An engineering connection is made to motivate students and relate the concepts they are learning to real-world applications. This connection is stated as follows: “Using math and science, engineers have been able to design sensors that impact our health and our safety. For example, sensors are used to activate airbags in cars during an accident. Also, engineers design smart sensors that can be attached to the helmet of a football player. The smart sensor can measure impacts experienced by the brain and transmit the data wirelessly to a base station that is monitored by a medical team. Engineers use the collected impact data to help manufacturers develop more protective helmets.”

Learning Activity 3 (Grade Level: 11, Subject: Physics)

The learning objectives of this activity are:

- To apply the engineering design cycle to create a product designed to achieve a specific goal
- To apply knowledge of electricity and circuits to correctly design a working sensor

- To make reasonable, quantitative conclusions from collected data, with physical interpretations, an assessment of uncertainty, and a discussion of the limitations of the conclusion
- To effectively document and communicate the process and results of their design work

This activity involves a complete engineering design that follows the main steps of the engineering design cycle. In this activity students follow the steps of the engineering design cycle and use their knowledge of electric circuits, sensors and mechanics to produce the best possible electric balance using a conductive rubber band as a transducer. Through experimentation, students learn that when a rubber band is stretched, its resistance increases. Students are then challenged to apply their knowledge of electricity and rubber band electric characteristics to produce the best possible electric balance to measure the mass of an object. The activity emphasizes the engineering design cycle and data collection, analysis, and interpretation skills.

The engineering connection developed for this activity states that "engineers apply their knowledge of science and math to solve problems by designing systems within certain constraints, producing prototypes which they evaluate and improve to achieve an optimal solution. Like engineers, students have the opportunity to use their knowledge of electric circuits and data analysis and follow the engineering design cycle steps that involve researching, designing, building, testing and evaluating an electric balance."

Lesson assessments (pre-activity assessment, activity embedded assessments, and post-activity assessments) were developed for each learning activity. Equipment, materials and supplies were provided by the professional development program to teachers to implement the learning activities in their classrooms. The learning activities were implemented in three different schools. Students worked in groups of 3 or 4. The cost of expendable materials per group is kept below 20 US dollars to ensure that the activities could be adopted by other teachers.

Summary

The engineering research experience provided the teachers with the confidence and knowledge needed to effectively implement the engineering educational activities. The process of developing the educational activities inspired by the engineering research experience required multiple iterations and regular discussions between teachers and the professional development program management team. The implementation of the engineering educational activities also required the cooperation of school principals who were very supportive of their teachers' work and participation in the professional development program. The visits to the teachers' classrooms provided an opportunity for the program personnel to observe the implementation of the engineering educational activities and provide feedback to teachers. These classroom observations are also used as a learning experience for the program management team to improve the effectiveness of the program in future cycles.

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