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Abstract

Engineering design activities can help educators to apply concepts and processes from within and across STEM domains. To facilitate these connections, there is a need for sustained, job-embedded, and collegial professional development that brings together teachers from across STEM domains to engage in design-based activities. These activities can help teachers better understand engineering design processes and can foster collaborations. This can lead to a culture shift within the school by which integration of STEM concepts and process becomes more seamless for both educators and their students. This paper describes a research-based model for professional development to promote engineering pedagogy to support learning of STEM concepts within and across domains.

Keywords

STEM, integration, engineering, professional development

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Abstract

Engineering design activities can help educators to apply concepts and processes from within and across STEM domains. To facilitate these connections, there is a need for sustained, job-embedded, and collegial professional development that brings together teachers from across STEM domains to engage in design-based activities. These activities can help teachers better understand engineering design processes and can foster collaborations. This can lead to a culture shift within the school by which integration of STEM concepts and process becomes more seamless for both educators and their students. This paper describes a research-based model for professional development to promote engineering pedagogy to support learning of STEM concepts within and across domains.

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Introduction

Science, technology, engineering, and mathematics (STEM) education disciplines call for students to apply concepts and process from within their respective domains to solve novel problems (International Technology Education Association [ITEA], 2000; National Council of Teachers of Mathematics [NCTM], 2000; National Research Council [NRC], 1996). Problem solving can be used to reinforce learning and provide evidence of far transfer (Bransford, Brown, & Cocking, 1999). As the use of STEM concepts and processes to solve problems is a key aspect of engineering (Accreditation Board for Engineering and Technology [ABET], 2005), engineering design activities can provide a pedagogical tool for educators to reinforce and extend learning (Barron & Darling Hammond, 2008; National Academy of Engineering [NAE], 2009). Engineering design activities provide students with relevant and engaging tasks in which they collaboratively work to intentionally employ STEM concepts and processes to solve problems. Engineering design activities can also be used as a space of discovery and inquiry before formal instruction about concepts and processes related to the problem begins. However, educators must be very intentional in selecting and facilitating understanding of concepts and processes that are applied (and/or explored) through engineering design activities.

Engineering design activities can also serve as an integrator between STEM domains (NAE, 2009). As engineers apply concepts and processes from across multiple domains, teachers and their students should also apply concepts and process across domains to solve novel problems. This “breaking down of the STEM silos” through engineering design activities can provide students and their teachers with an opportunity to see how concepts and processes from multiple domains can

be used within design processes (e.g., problem formation, predictions of prototype testing, and analysis of prototype testing). This also provides a valuable opportunity for teachers from across STEM domains to support, by intention, the learning of concepts and processes from outside of their respective domain. Yet, caution should be taken that this support does not supplant learning from outside domains.

Research Supporting Engineering Design within STEM Domains

Policy documents have called for the integration of STEM domains through activities such as engineering design (American Association for the Advancement of Science [AAAS], 1993; ITEA, 2000; NRC, 1996). Research supports the call for integration through pedagogies, such as engineering design, to improve learning within and across the STEM disciplines. A review of studies related to the integration of engineering into science and mathematics education (NAE, 2009) found that engineering design pedagogy is related to improvement of student learning and achievement within these respective domains. In addition, this review found a link between engineering and improved achievement of diverse learners.

Reviews of research on integrated approaches to instruction further support integrated STEM education approaches anchored in engineering design. Mathison and Freemond's (1997) review of research found that integrated curriculum benefits students' understanding and abilities to transfer concepts toward solving novel problems, critical thinking and problem solving skills, motivation, and helps foster better understanding of connections between and beyond disciplines. In addition, literature on problem-based learning, which has close ties to the authentic design work of engineers (Mills & Treagust, 2003), provides further potential evidence for integrated STEM education through engineering design. Reviews of problem-based learning studies (Barron & Darling-Hammond, 2008) find that problem-based instruction provides similar results to traditional instruction-related factual learning. However, problem-based learning excels in developing student problem-solving abilities, application of knowledge, hypothesis generation, citation of evidence, and conceptual understanding (Barron & Darling-Hammond, 2008). This collective evidence, although limited as related to engineering pedagogy (NAE, 2009), supports the value of engineering design as an integrative pedagogy to improve student learning within the STEM domains.

In order to use engineering design pedagogies effectively, many STEM educators need professional development (Bybee & Loucks-Horsley, 2009; NAE, 2009). They must better understand the authentic work of engineers and their use of iterative design cycles to develop new technology defined as any product or process that has

been developed to solve a human want or need (AAAS, 1993; ITEA, 2000; NRC, 1996). They must also see how the concepts and processes from within their domains are used to develop technology and understand how to use design-based pedagogy in various phases of instruction (e.g., for applications of concepts, for discovery of concepts, etc.) to support learning of these concepts. Finally, teachers are in need of a broader understanding of how concepts and process from other STEM domains can be used to support learning within their domains. This requires a more robust and refined understanding of how engineering and other content areas intersect and inform their own pedagogical content knowledge (Shulman, 1986). Research-based professional development is required to help facilitate the development of educator knowledge of engineering design pedagogy and its power to foster learning within and across STEM domains.

A Professional Development Model to Foster Engineering Pedagogy and STEM Integration

This paper will describe a professional development model developed by the author to promote STEM integration through engineering design pedagogy. This model is grounded in research on professional development and has been refined through implementation and evaluation in several contexts. Research-based professional development is framed as job-embedded, collegial, and sustained over an extended period of time (Wei, Darling-Hammond, Andree, Richardson, & Orphanos, 2009). In this model, teachers from STEM domains are brought together to form collegial professional learning communities (PLCS) (DuFour & Eaker, 1998) as to create a space in which teachers can collaboratively learn from and with each other over extended periods of time.

The purpose of this model is to develop knowledge of engineering and engineering design pedagogy for STEM educators, and to begin conversations within interdisciplinary PLCS as to how engineering can support learning within and across STEM domains. In essence, this model works to build topic-specific pedagogical content knowledge related to engineering and engineering design. In this model, teachers experience engineering design activities, designed for adult learners, to learn the processes of engineering design and to make the connections to their own content areas. This model follows a learning cycle that solicits prior knowledge, provides direct experiences with phenomena, and provides sense-making experiences to reflect on changes in knowledge. Within this model, teachers collaborate to explore connections to other content areas.

The following sections will describe components of the model and will provide examples of how this model can be enacted within professional development settings. Many different design-based activities can be used in this model.

The professional development example used in this paper uses a design-based challenge in which participants design and test straw rockets. The author has used this activity with several secondary STEM educators professional development settings. It is not necessarily the design challenge that is important, but the discourse it fosters. This model has also been used with primary educators, but for the purpose of using engineering design pedagogy as an integrator between teachers, it is discussed here for use with secondary science, mathematics, and technology educators. The following diagram (Figure 1) highlights the first five phases in this professional development model. It is important to note that the example provided is a somewhat brief experience; it is not intended that this activity stand alone—it is to be used in an integrated STEM professional learning community. This experience provides a starting place for further collegial conversations and job-embedded experiences as part of PLCs as described at the conclusion of this paper.

Explore Prior Knowledge Related to Engineering and Relationships Between Domains

The first phase of the professional development model engages teachers' prior knowledge and beliefs from both a content-knowledge and pedagogical-knowledge perspective. Open-ended questions are posed in a "think, pair, share" format (Lymna, 1981) in which participants individually reflect on open-ended questions, work in small teams to discuss the question, and then explore the question in a large group discussion. Questions ask participants to explore the similarities and differences between technology, science, mathematics and engineering as well as the role of mathematics, science, and technology within engineering design. Participants also discuss if teachers can be classified as engineers.

During this phase, it is critical not to provide "correct" responses but to allow the knowledge to be refined and built throughout the experience. This group knowledge is

captured and referred to throughout the activity as new knowledge is developed and refined. This information also provides formative assessment information for the facilitator that is used to inform the pacing and emphasis of concepts in subsequent phases.

Develop Basic Knowledge of Engineering

In this phase, participants are engaged with broad concepts and processes related to the practice of engineering. The purpose of this phase is not to provide a detailed understanding of engineering knowledge, but to provide enough knowledge so that the participants can more thoughtfully engage in an engineering design activity. Further follow up professional development activities can be used to develop greater knowledge of engineering and engineering pedagogy at a later time.

Participants are first engaged with formal definitions of technology. For the purposes of this activity, technology is defined as any product or process that has been developed to solve a human want or need (AAAS, 1993; ITEA, 2000; NRC, 1996). Questions are then posted to educators as to "look around" their world and think about what is, and what is not, technology. This definition provides space for educators to imagine a broader world of engineering, beyond what many typically think of as mechanical engineering, and to see broader connections to the work of engineers and their content areas.

Participants then learn formal definitions of engineering. Engineering is defined as the "profession in which a knowledge of the mathematical and natural sciences... is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind" (ABET, 2005) and engineering as the process by which the technology is designed. These broad definitions of engineering and technology allow the participants quickly to see a relationship between science, mathematics, engineering, and technology. This also allows these STEM educators to see that they may have already

Figure 1. A Professional Development Model for an Engineering Design Experience to Foster STEM Integration.

used engineering pedagogy within their practice through the application of science and mathematics toward solving design problems.

Participants are then provided with a list of approximately twenty different engineering domains. This allows these STEM educators to see the diversity and broad impact of engineering. Participants are then engaged with questions that allow them to see how different fields and different types of engineers work together collaboratively. For example, participants can be asked about the different fields of engineering such as civil, biological, mechanical, electrical, and others that work together on the NASA space shuttle (Polenberg-Thomas, 2010).

Finally, in this knowledge-building phase, participants are shown different engineering design cycles used in K12 education (e.g., Engineering is Elementary, Design Squad, Engineering the Future). Participants are then asked to find the similarities between the design cycles. Through this, participants should recognize the importance of iteration within all of the displayed design cycles. Participants can then be re-challenged to explore if they believe that educators are engineers based on their new understandings (e.g., teachers can be classified as instructional designers or instructional engineers due to their use of a theoretical knowledge base and the use of data to guide the iterative process of curriculum development). Other initial conceptions of engineering and technology developed in the first phase should also be reviewed at this time to note changes or refinements of knowledge.

Engage in Cooperative Engineering Design Activity

In this phase, participants engage in a cooperative engineering design activity. It is important to note to the participants that this activity is designed for adult learners and is not intended for direct use in K-12 classrooms. This activity is designed to provide an experience that can add to their content and pedagogical knowledge related to engineering design. However, participants are free to adapt this activity to their classrooms.

Participants are provided with a design brief that provides a relevant and engaging problem. In the case of the straw rocket challenge, the participants design an air-powered rocket. (This can be framed as a small-scale prototype that could be used to better understand larger rocket systems in order to improve the design of water- and chemical-powered rockets.)

Participants are provided with criteria, or specifications to be met, and constraints that are limiting factors to consider. In the case of the straw rocket challenge, the criteria include a minimum distance to travel (i.e., 5 meters) and required design components (i.e., include at least one fin and nose cone). Constraints for this activity include use of provided materials (i.e., straws, clay, note card materials and tape), the development of a rocket that fits on the

launcher, and limited time to design, build, and test. A sample commercially available launcher (Pitsco, 2010) that allows for precision angles and launch force is shown below (Figure 2).

For the straw rocket activity, an additional challenge is introduced before design work begins. Participants are told that, after a specified amount of development and testing time, which allows for multiple iterations, they will be presented with a final challenge. A target, such as a bucket, will be placed at an unknown distance between 5 and 20 meters. Teams must launch their rocket so it lands in the bucket with only one launch. This additional level of complexity forces groups to collect additional levels of data during testing, to seek patterns in the data, and to make decisions on which system variables to control to achieve this goal.

For this activity, participants are placed in assigned, cooperative learning (Johnson, Johnson, & Holubec, 1998) interdisciplinary teams of three to four. Teams should include representatives from mathematics, science, and technology education. Roles such as facilitator, recorder, material manager, are randomly assigned.

Figure 2. Straw Rocket Launcher and Supplies.

Finally, before design begins, participants are prompted to think about individual content and pedagogical connections from the perspective of an educator throughout the activity. Questions such as “What science, mathematics, and technology concepts and process might an activity like this develop?” and “What other benefits would an engineering design activity such as this have for students?” are posed before design begins. It is important to have the group facilitators and recorders engage group members with these questions during and after the design process. This engages the participants to think both as learners of engineering concepts and practices as well as practitioners who will use engineering design pedagogy.

During this engineering design challenge, participants are encouraged to follow a design cycle (Figure 3) (WGBH Educational Outreach Department, 2007) and to document their processes, as well as questions related to design and testing. To prompt greater diversity of ideas from within these groups, each of the participants is asked to sketch out at least two unique rocket designs. Elements of these designs can be discussed and evaluated based on the criteria and constraints. Throughout the design process, the professional development facilitator monitors all groups and asks probing questions that solicit participants to make explicit their design and redesign decisions and to make STEM content connections.

The activity is paused occasionally so questions and sharing of design ideas can be discussed across groups. This is important to limit the level of group competition and to build community and knowledge across groups. Participants are encouraged to share designs to improve the collective designs. (This video (Donna, 2009) highlights the importance of the facilitator posing questions throughout the design and provides an overview of the design and follow-up reflections (<http://tinyurl.com/int-STEM-rockets>).)

Reflect on Activity as Both Learners and STEM Educators

During this phase of the professional development activity, participants engage in reflection within and across content area groups to discuss how activities such as the straw rocket challenge could be used to intentionally develop and/or apply concepts from within their individual domains. Reflection first starts in their interdisciplinary groups and then continues in disciplinary groups. Finally, the groups report from a large group brainstorming and discussion session. The following is a set of themes based on participant responses from several professional development settings based on the straw rocket activity. These themes are framed by standards within STEM domains (ITEA, 2000; NRC, 1996; NCTM, 2000):

Connections to Technology Education Concepts and Processes:

1. Systems modeling (e.g., examining rocket and/or launcher as a system).

Figure 3. Design Squad Engineering Design Cycle.

2. Historical perspectives on technology (e.g., history of ballistics and rockets).
3. Technological concepts such as levers, energy transformation, pneumatics, and aerodynamics.
4. Design processes.
5. Evaluating criteria within optimization processes (trade-offs).
6. Brainstorming, decision making, problem solving.

7. Construction of prototypes to be used for scaled-up production.
8. Marketing.
9. Communication of technical, constructional, conceptual, and aesthetic design.
10. Evaluation of social, economic, and environmental impacts.

Connections to Mathematical Concepts and Processes:

1. Measurement within design and analysis.
2. Scaling (for actual designs and scale up of designs).
3. Development of tables and graphs.
4. Examination of patterns within data tables and graphs.
5. Statistics (e.g., analysis of data from within the group or large class statistical analysis).
6. Using mathematical analysis for decision making.
7. Interpolation or extrapolation (e.g., deciding how to land in the bucket with one shot using graphs).

Connections Science Concepts and Processes:

1. Concepts of energy transformation, projectile motion, and levers (used to inform design and analysis).
2. Controlled experimental design (e.g., single variable manipulation).
3. Data analysis (through the use of science principles).
4. Qualitative and quantitative observations and inferences.

In this phase, participants also discuss potential benefits of this type of engineering pedagogy. Based on several participant conversations, participants have expressed that engineering design can help provide:

1. Conceptual links across domains.
2. Context and motivation to apply concepts across STEM domains and other domains such as social studies.
3. Cooperative learning experience.
4. Communication experience.
5. Problem solving and optimization skills.
6. Failure management (learning to learn from failure) skills.
7. Multivariable and systems thinking skills.
8. Opportunities to value multiple solutions and to value simple solutions.
9. Opportunity for creative and informed play (enjoyment).
10. Potential career pathways.

Extend Knowledge and Connections Between Domains

In this phase, participants continue to refine their knowledge of engineering as it relates to their own domains and begin to refine their own pedagogical knowledge as they make connections across domains. Participants first

return to the initial discussions of the similarities and differences between technology, science, and mathematics. Formal definitions for mathematics and science are provided at this time. Participants discuss the conceptual links between science and technology (see AAAS, 1993; ITEA, 2000; NRC, 1996; Boston Museum of Science, 2008) by reflection on the diagram below (Figure 4). Examples such as how the scientific concepts related to optics lead to engineering microscopes, which allowed for greater scientific exploration, are discussed.

Participants then shift from building content knowledge to building pedagogical knowledge. Moving between content knowledge and pedagogical perspectives builds pedagogical content knowledge related to engineering and allows participants to think how engineering design pedagogy could be used to develop, by intent, specific concepts and processes within their individual domains. At this time, teachers discuss how they would modify the design activity for use in their course to intentionally help students learn course concepts and processes. For example, a science educator could transform the straw rocket professional development activity for classroom use to teach science concepts and/or processes. Straw rockets could be used in a guided inquiry investigation in which groups of students could be assigned particular variables to investigate (e.g., weight, number of fins, length of rocket). The educator could then engage students in a more open-ended design in which they use knowledge developed during this experience to inform their design. This could help to develop skills of experimental design as well as to develop conceptual understanding of concepts such as projectile motion.

During this discussion, participants also think about how and when to use engineering design activities to develop or apply knowledge from within their domains. For example, in science education, engineering design pedagogy can fit in multiple places within the 5E instructional model (as described in Bybee et al., 2006). Straw rockets can be used as an introductory 'Engagement' activity that can provide fertile ground for developing questions and interest related to science concepts such as force. This activity could also

Figure 4. Relationships Between Science, Engineering, and Technology.

be used in the 'Extension' phase, when students apply concepts (energy transformation) toward solving a novel problem (rocket design). Regardless of sequence, teachers must help facilitate thoughtful content connections through design activities.

These types of discussions allow educators to explore not only how design pedagogy can be embedded in their own instruction, but also how they may support learning across other STEM domains. This can begin conversations between STEM educators within interdisciplinary PLS as to the similarities and differences between pedagogies, purposes and standards within science, mathematics, and technology education in order to seek natural connections. In addition, science and mathematics educators can engage in discussion as to where their respective domains can be used within the processes of engineering design. For example, concepts of science play a critical role in informing initial design as well as in understanding the results of testing; mathematics plays a critical role in the testing phase. These conversations allow for deeper, more intentional and thoughtful application of engineering design pedagogy and can begin conversations as to how educators from other domains can help support learning across domains.

Evaluation

While formative evaluation should be continuous throughout the activity, a formal evaluation, such as a written KWL or "Know, Want to Know, and Learned" activity, can provide valuable information for the professional development facilitator which can help refine the activity and can help guide the next activities. This also provides an opportunity for participants to make sense of the experience and look for next steps to further their own learning. In addition, evaluation can be used to understand what teachers may see as barriers and pathways toward STEM integration through engineering design pedagogy.

Exploratory qualitative analysis of four secondary education implementations of this activity suggests that participants can better understand connections between disciplines through design experiences. One participant commented: "how easy it can be to [link STEM domains] together. It is not as difficult as I thought it could be." Participants have also commented about how they would now like to begin collaboration between STEM colleagues. For example, one participant states that the next step "will be to start a collaboration with my math and science programs to see what we can share and build on." Further qualitative research should be conducted to understand the ways engineering design professional development activities promote development of pedagogical content knowledge which allow for the integration of ideas within and across domains and support integrative, collaborative practices.

Conclusion

Professional development experiences that allow interdisciplinary teams of teachers to engage in engineering design activities can help promote connections within and across STEM domains. However, the activity described in this paper should only be a part of a comprehensive, sustained approach to teacher professional development. One experience is not sufficient to build teacher knowledge and skills, nor to impact teacher practices, without continued professional development experiences. Extended professional development through the use of interdisciplinary PLCs can be used to help further the collaboration between STEM teachers and to promote interdisciplinary practices within and across courses.

Professional learning communities can provide a space in which teachers develop engineering design activities for use in their classrooms and then return after implementation to collaboratively reflect upon and improve their practices. In this space, teachers across STEM domains can also work with each other to improve meaningful connections between the domains. For example, STEM educators could develop a common engineering design activity for use with their students. They could then use the activity for different purposes of developing or applying content knowledge from within and across their respective domains. They can then return to collaboratively reflect on implementation through analysis of student work samples and other data.

Other PLC activities, such as book studies on interdisciplinary curricular development (see Drake, 2007) and unpacking of the individual STEM standards can be used to further teacher knowledge of interdisciplinary thinking through engineering design. In addition, it should be noted that engineering design activities are only one potential integrating pedagogy for STEM education. Other approaches, such as case study pedagogy, can be developed within these PLCs. Information technology, such as wikis and other cloud computing tools, can be used as a space where teachers can collaborate and communicate between PLC meetings. Information technology could also be used to help foster collaboration between teachers across districts who may have smaller numbers of colleagues.

It should be noted that professional learning communities require substantial time and space to foster such collaboration between educators. PLCs place power and responsibility on teachers to direct their own professional learning and require significant efforts on the parts of school and district leaders to help those teachers build the community required for this work. This requires investment from districts and schools and requires support from administrators and policy makers.

With sustained, job-embedded professional development, engineering design pedagogy can help foster integrated approaches to STEM education. This can not

only help educators to make meaningful connections toward developing STEM literacy for their students, it can also help change the culture of a school as educators begin to work together to find and act on commonalities that can support learning within and across their respective domains.

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