Abstract

An Engineering Innovation Tool was designed to support science teachers as they navigate the opportunities and challenges the inclusion of engineering affords by providing a useful tool to be used within the professional development environment and beyond. The purpose of this manuscript is to share the design, development and substance of the tool that has been used in two engineering-oriented teacher professional development projects. The tool has strong potential to help educators and teacher professional development providers navigate the engineering component of secondary-level science education.

Keywords: teacher professional development, science, engineering

Science teachers are being tasked with including engineering practices, cross-cutting concepts with science, and core engineering ideas with the adoption of the Next Generation Science Standards (NGSS) (Achieve, 2013). The inclusion of engineering in the K-12 curriculum is seen as an effective strategy for combating declining test scores and engaging students by providing real-world contexts within which students can learn (Brophy, Klein, Portsmore, & Rogers, 2008; Katehi, Pearson, & Feder, 2009). The approach of embedding science content into appropriate and meaningful contexts relates to the need for the K-12 system to produce students who are able to combat the complex ‘wicked’ global challenges they will face (English, 2016; National Academy of Sciences, National Academy of Engineering, and Institute of Medicine of the National Academies, 2006; Pinski & Baranyai, 2015). There is also the desire to stimulate STEM (science, technology, engineering, and mathematics) career interest in more students, particularly those from underrepresented populations (Brophy et al., 2008; Katehi, Pearson, & Feder, 2009).

While the inclusion of engineering in the NGSS has the potential for enhancing student learning, this approach is particularly challenging for science teachers who have little background or familiarity with engineering. Professional development and instructional support resources are slowly emerging, especially in regard to the engineering components of the standards. Access to engineering-infused science teacher professional development, however, is limited by availability and funding (Brophy, Klein, Portsmore, & Rogers, 2008; Moskal et al., 2007; Yoon, Diefes-Dux, & Strobel, 2013). And curricular resources that integrate engineering into science are not yet abundant. Even with the available resources, teachers need to know what engineering looks like in the science classroom. A crucial step in implementing curriculum that is in alignment with the NGSS is access to additional instructional resources, professional development, and a positive school culture (Smith & Nadelson, 2017). Teachers eager to implement the NGSS are in need of tools and techniques that will support their ability to visualize what engineering might look like in their classroom. An Engineering Innovation Tool (EIT) was designed to provide a picture of what engineering design looks like in science by drawing from documented best practices.

The purpose of this manuscript is to share the design, development, and substance of the EIT so it can be used to support professional development providers, curriculum developers, and teachers as they implement the NGSS. The EIT has been successfully used in two NSF funded engineering-oriented teacher professional development projects (Project Infuse and INSPIRES Program). Based on its design, refinement, and successful application, the EIT has strong potential for serving as a useful tool to help educators and teacher professional development providers navigate the engineering component of secondary-level science education. A description of how the tool was designed and developed is provided, followed by a presentation of the EIT. The paper concludes with a description of how the EIT was successfully used in the three different contexts.

Background

The challenge presented by the transition to the NGSS for teachers is substantial. Not only is engineering now included within the domain of science instruction, the three-dimensional learning approach of the standards requires a shift for teachers. Thus, the National Research Council (2015) advocated for a multiyear teacher professional development plan. As Reiser (2013) argued, even with new curriculum materials and assessments, “without a strong focus on aligned professional development, adopting NGSS and providing these resources will not be sufficient” (p. 2). Strategies for effective teacher professional development (PD) have been explored in the research literature for decades (Darling-Hammond & McLaughlin, 1995; Garet, Porter, Desimone, Birman, & Yoon, 2001; Guskey, 2003). Desimone (2009), for example, outlined five characteristics of effective PD: content focus, active learning, coherence, duration, and collective participation. The targeted outcomes of the professional development are largely focused on the teacher; their content knowledge, pedagogical skills, and sense of self-efficacy.

The engineering component of the NGSS is particularly challenging for science teachers as they transition to the NGSS. There are some studies that have examined engineering-oriented professional development (i.e., Daugherty, 2009; Guzey, Tank, Wang, Roehrig, & Moore, 2014; Yoon, Diefes-Dux, & Strobel, 2013). A key issue for the engineering element has been how to define or approach engineering at the K-12 level, especially for teachers unfamiliar with engineering. Moore, Glancy, Tank, Kersten, Smith, and Stohlmann (2014) addressed this need by creating a framework to be used to guide the development of curricula, classroom implementation, standards, and policy of engineering in K-12 STEM education settings. Similarly, the EIT emerged from a need identified by a group of teachers engaged in an engineering-oriented teacher professional development research project, Project Infuse.

Project Infuse was a National Science Foundation-funded research project that developed, delivered, and researched engineering-oriented teacher professional development to two separate groups of teachers; one group of physics teachers and one group of biology teachers. Two cohorts of science teachers participated in a series of summer institutes and school year activities for two years. Teachers engaged in the Project Infuse teacher professional development program asked for a way to
“see what engineering looks like” in a science classroom. Although they had access to existing engineering-infused science curriculum and models, case studies, and design challenges, they desired an additional tool that indicated the defining features of engineering design implementation across a variety of implementation levels. The EIT was developed by the project’s leadership and participating teachers to indicate the essential (and often missing) components of engineering-infused science. The primary goal of the EIT is to provide teachers with a clear vision of the distinguishing features of practice-based, engineering-infused teaching. The EIT is not a research or evaluation tool nor is it an assessment; it is meant to serve as a support to science teachers as they infuse engineering design.

**Design & Development**

The primary goal of the EIT was to provide teachers with a clear vision of the distinguishing features of engineering-infused teaching. The process of designing the tool roughly followed these chronological steps: (a) reviewing materials used within the professional development program (curriculum, case studies, engineering design models, etc.); (b) observing teachers implement engineering lessons in their classrooms; (c) generating a list of possible components that represent the essential aspects of engineering-infused science; (d) clustering suggestions that are similar and creating one statement to represent each set of the suggestions; (e) agreeing on which components are key and should be developed; (f) developing the wording of components and component variations; and (g) testing the draft tool for a “dose of reality” to identify points that need clarification and other components that need to be included.

Once the framework for the tool was designed and iterated among the project leadership team, the pilot cohort of Project Infuse teachers was included in the development process. This involvement occurred primarily during the second summer institute as part of their professional development and to leverage the teachers’ experience in science classrooms to refine the tool. It should be noted that one key point of deliberation during the development process was whether the focus should be (a) on teachers and their observable behaviors, (b) on students and their behaviors, or (c) a combination of the two. Although a distinction between teacher and student understanding and behavior is difficult to determine, the tool is intended to be interpreted from the teacher’s perspective to support teachers as they engage in engineering infusion.

**An Engineering Innovation Tool**

Three categories emerged as particularly important to provide teachers a clear vision of infusing engineering into science. These focus areas are: (a) curriculum materials; (b) design-centered teacher practices; and (c) engagement with engineering concepts. After the three categories were defined, the leadership team developed descriptions of what implementation would look like across a spectrum of alternatives. These descriptions represent the operational forms that have been observed as engineering infusion is implemented in the classroom. Different ways of doing engineering infusion were captured as levels for each sub-component within the tool. Four levels were used for each sub-component to describe a range from more to less desirable implementation. Collectively, this process yielded a set of “word-picture” descriptions structured within a well-developed conceptual implementation framework.

As shown in Table 1, the tool guides teachers through evaluating the engineering components of the selected curriculum in that they should include engineering concepts, an open-ended design challenge, and be designed to facilitate the connection between engineering concepts and science learning. Materials should be standards-based and include a student assessment component. The ability to analyze and select curriculum materials based on the materials’ strengths and weaknesses is an important element of incorporating an educational innovation (Beyer & Davis, 2012). An essential component of effective integration of engineering into science is the selection of quality instructional materials that make explicit links to science learning outcomes. Curriculum materials chosen by the teacher should include engineering concepts, include an open-ended design challenge, and be designed to facilitate the connection between engineering concepts and science learning (Brophy et al., 2008; Cunningham & Carlsen, 2014; Hmelo, Holton, & Kolodner, 2000). As the 2014 NAE/NRC committee concluded, the curriculum also needs “to carefully frame the instructional goals and settings to support students in making links to concepts in science” (Honey, et al., 2014, p. 58).

The other two categories of the tool target pedagogical practices that occur in the classroom include design-centered practices and engagement with engineering concepts. The primary approach of infusing engineering into science is through design challenges and

### Table 1. Category 1 of the EIT

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<td>A1. Curriculum targets engineering concepts articulated in science standards appropriate to the level of instruction.</td>
<td>Curriculum targets engineering concepts articulated in science standards, but the concepts targeted are not well-matched to the level of instruction.</td>
<td>Curriculum targets engineering concepts, but the concepts targeted are not science standards-based.</td>
<td>Curriculum does not target science and engineering standards.</td>
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<td>A2. Materials chosen include at least one open-ended engineering design challenge that requires understanding of scientific concepts and an iterative process for optimal solutions.</td>
<td>Materials include an engineering design challenge that requires understanding of scientific concepts for solutions, but the scientific concepts are not those targeted by the teacher (unit, standards).</td>
<td>Materials chosen do not include an open-ended engineering design challenge.</td>
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<td>A3. Curriculum materials make explicit connections between engineering concepts and science learning.</td>
<td>Curriculum materials include engineering concepts, but connection to science learning is not explicit.</td>
<td>Curriculum materials lack explicit engineering concepts.</td>
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<td>A4. Materials include a standards-based student assessment that explicitly targets both science and engineering concept understanding in an authentic context.</td>
<td>Standards-based student assessment is included and targets engineering concepts, but coverage of engineering concepts is minimal or exclusively at the knowledge/comprehension level.</td>
<td>Student assessment includes engineering concepts, but is not in line with appropriate standards.</td>
<td>No evidence of student learning assessment that includes engineering concepts.</td>
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engineering concepts. Table 2 focuses on design-centered teacher practices where the teacher assumes the role of consultant/guide to support student teams as they use a rational design process. The design challenge should be structured as an open-ended team-based activity where each team generates a unique solution. In order to support science learning, the teacher should make explicit connections to science concepts when supporting design teams and routinely ask students to provide science-based rationale for design decisions (Crismond, 2001; Crismond & Adams, 2012; Cunningham & Carlsen, 2014; Fortus, et al., 2004; Fortus, et al., 2005; Hmelo, Holton, & Kolodner, 2000; Household & Hailey, 2012; Nadelson, Pfiester, Callahan, & Pyke, 2015).

The third category shown in Table 3 focuses on teacher practices that target student engagement with engineering concepts. Teachers should make explicit connections to engineering throughout the lesson/unit and routinely use appropriate engineering terminology. Teachers should explicitly connect science concepts with real-world engineering applications and describe these applications as the rationale for the learning of science. Use of terminology is a best practice that makes engineering and science concepts explicit to students during the implementation of the lesson (Custer, Daugherty, & Meyer, 2010; Massouw, Hacker, & de Vries, 2011).

Table 2. Category 2 of the EIT

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<td>B1. Teacher structures the design challenge as a team-based activity such that all team members contribute to the design solution. Checks and balances are in place to ensure that all participate.</td>
<td>Teacher structures the design challenge as a team-based activity, but checks and balances are not always effective to ensure that all students participate.</td>
<td>Teacher structures the design challenge as a team-based activity, but checks and balances are not in place to ensure that all students participate.</td>
<td>Design challenge is structured as an individual activity</td>
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Examples of “checks and balances” include the teacher actively asking about participation as he/she moves from group to group, assigning individual students to play specific roles during the design challenge, including a peer rating system in students’ report-out and/or grade, and/or requiring each student to report out on results.

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<td>B2. Teacher encourages a unique solution from each team and actively supports students in creating a unique solution during the design process.</td>
<td>Teacher encourages a unique solution from each student in the activity’s introduction, but does not actively support students in creating a unique solution during the design process.</td>
<td>Teacher does not provide direction to students regarding “uniqueness” of design solution.</td>
<td>Teacher actively directs students toward a single solution.</td>
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Open ended design challenges have multiple solutions and in engineering it is desirable for a design to have attributes that differentiate it from competitors. The word “unique” as used above is meant to capture this element of engineering design. In the best case scenario, there would be some element or attribute to each group’s design that is a bit different from all the others. In other words, something that differentiates it and makes it “unique”.

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<td>B3. Teacher actively checks on group progress and provides individual coaching to groups by making specific suggestions for additional considerations or next steps.</td>
<td>Teacher actively checks on group progress and provides general coaching to the class as a whole rather than on an individual group basis.</td>
<td>Teacher observes group work to check on progress but does not provide coaching at either the class or individual group level.</td>
<td>Teacher neither checks on group progress nor offers coaching to support group work.</td>
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<td>B4. Teacher requires students to engage in an iterative design process with at least one opportunity for redesign, testing, and analysis.</td>
<td>Teacher requires one cycle of redesign on paper but does not include testing or analysis of the new design.</td>
<td>Teacher requires students to briefly document what they would do differently if allowed to redesign.</td>
<td>No evidence of redesign.</td>
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The tool was also used to structure an analysis and review of a series of classroom implementations. Specifically, the EIT was used to select clips from videotaped lessons conducted by the teachers during the school year for use during the second summer’s institutes. The tool provided a mechanism for selecting a range of implementations from exemplary to those that missed some significant instructional opportunities. Selected video clips were woven together into a video using the tool as a structure. These were used during the institutes to reinforce and explore understandings of engineering infusion. The EIT served as a tool for guiding teachers in their thinking about, discussing and assessing engineering infused curricula, exploring personal teaching practices, and planning how to infuse engineering content and activities into their courses and lessons.

As discussed earlier in the paper, the Engineering Innovation Tool was developed to assist the teachers in the professional development to “see” what engineering might look like in their classrooms. The EIT was used as a communication and conceptualization tool in the professional development environment. Consistent with best communication practices, this was a two-way interaction between the leadership team and the teachers. Teacher interaction with the tool provided a mechanism for clarifying what is meant by engineering infusion and for improving the content of the tool. Ultimately, the EIT served as a tool for guiding teachers in their thinking about, discussing and assessing engineering infused curricula, exploring personal teaching practices, and planning how to infuse engineering content and activities into their courses and lessons.

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Context 1: Teacher Professional Development Tool

The primary focus of the Project Infuse teacher professional development was on key engineering concepts (i.e., design, analysis, systems, modeling) to build a deeper understanding of engineering (Custer, Daugherty, & Meyer, 2010). Concepts provided a touchstone for the teachers to understand engineering and entry points for its inclusion into their curriculum and instruction (Custer, Eisenhower, Wendell, Daugherty, & Ross, 2016). During the summer institutes, teachers were engaged in three major categories of experiences, including: (a) conceptual development, (b) curriculum infusion, and (c) classroom preparation (Custer, Ross, Daugherty, & Peterman, 2014). Activities designed to develop the teachers’ conceptual understanding of engineering included case study analysis, concept mapping, and engineering design analysis activities.

Teachers were engaged with existing engineering-infused science curriculum, as well as engaged in activities focused on developing engineering infused lessons. This was challenging due to the relative lack of availability of engineering-infused science curriculum materials. This void was particularly evident with secondary level biology in addition, a significant portion of the professional development was focused on classroom preparation activities including implementation plan development and critical reflection. During the school year, teachers delivered the engineering infused lessons and participated in workshops to debrief implementation successes and challenges.

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characterize the benefits and limitations of utilizing a curriculum-based professional development system as a mechanism for strengthening teacher pedagogical skills for integrating engineering into high school STEM classrooms. Success is measured by enhancement of teacher pedagogical skills and content knowledge, as well as student learning gains.

The EIT and the Reformed Teaching Observation Protocol (RTOP) were chosen to assess teacher pedagogy in a longitudinal study. While the RTOP measures “reform-based instruction” in general, the EIT focuses specifically on the pedagogical skills needed to infuse engineering into STEM classrooms. For use in this study, the EIT wording in section C was modified to include both science and mathematics concepts and the instrument was changed to a five-level scale. Adding the fifth level enabled the EIT to describe teacher pedagogical skills associated with integrating engineering practices and core ideas in high school STEM classrooms has enabled the project to measure changes and development as a function of the professional development and curriculum enactment experience. It has also allowed the project team to identify key pedagogical skills that need enhanced support for development. As such, the information from the EIT was used to inform decisions about the content of professional development; thus, aligning with its purpose as a teacher tool.

**Context 3: Evaluation of Lesson Plans**

The third context was a research study that used a variation of the Engineering Innovation Tool entitled the “Engineering-Infused Lesson (EIL) Rubric” to explore the utility of the tool in relation to online science lessons that are readily available to teachers (Peterman, Daugherty, Custer, & Ross, 2017). Online lesson repositories are a logical starting place for teachers who are searching for science lessons that also include engineering. The EIL Rubric was used to document whether and how best practices were infused into these types of engineering-oriented science lessons. As with the EIT, the EIL Rubric focused on engineering characteristics of the lessons to identify best practices in relation to the three general categories: Curriculum Materials, Design-Centered and Engaging Concepts.

Eighty lessons were selected at random from three online repositories and coded with the rubric. Scores were then calculated to document the average level of alignment to each of the three categories. Low scores were found overall for evidence of best practices related to Curriculum Materials. Scores were moderate for the overall categories of Design-Centered and Engaging Concepts category. A wide range of scores was found for the individual best practices aligned with these categories, indicating the utility of the EIL Rubric for documenting the variability of engineering infusion found in lesson plans. Further, these results highlighted the specific strengths and areas for improvement in the lessons coded. The strengths included lessons’ focus on NGSS science, and the utility of authentic real-world problems to frame learning for students. When design challenges were included, the level of teamwork in those challenges was high, consisting of the full range of best practices. Areas of improvement centered on a need for content and teaching practices to make explicit connections between science and engineering. This trend was found across the three components of the protocol.

The variability in scores for individual lessons was also used to identify the particular features that distinguished lessons that earned the highest scores on the EIL Rubric. These features included alignment to the NGSS engineering standards, the inclusion of an open-ended design challenge, explicit instruction related to engineering terminology, the use of authentic assessments, and assessments that focused on both science and engineering.

The EIL Rubric offers a practical application of an element of the EIT that enables teachers and researchers to document the strengths of online lessons and identify key areas that might benefit from the infusion of additional best practices from the field of engineering education. As such, the EIT can be used by teachers to identify promising lessons that are already available online or to guide the development of new lessons that infuse best practices from engineering education. We also anticipate that the EIL Rubric will provide a useful tool for the continued study of engineering lessons, particularly as more science materials are developed to align with the NGSS engineering standards.

**Discussion & Implications**

The Engineering Innovation Tool was one of the most beneficial outcomes of Project Infuse, with applications to other curriculum and professional development projects and research studies. The numerous conversations among the leadership team and with teachers served to move the engineering concepts from the abstract into the real-world contexts of teachers. During one phase of the teacher professional development, teachers were provided video-clips of their classroom instruction as illustrations of specific elements of the EIT. These clips were designed to

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<td>C1. Teacher makes explicit connections to engineering concepts throughout the lesson/unit (i.e., in the lesson introduction, primary activity, and wrap up)</td>
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<td>C2. Teacher uses engineering terminology correctly and provides explicit instruction on terminology to students.</td>
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<td>C3. Teacher provides rationale for science learning throughout the lesson by using real-world engineering application(s) OR focusing on the science needed to solve a real-world engineering challenge.</td>
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<td>C4. Teacher routinely asks students to provide scientific and/or engineering rationale for design decisions and supports students in developing detailed, correct responses.</td>
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Table 3. Category 3 of the EIT
illustrate strong points, as well as missed opportunities. The framework, language and “word picture” of the EIT yielded a rich range of discussions focused on engineering concepts and practice, the value of engineering in enhancing science instruction, pedagogical practices, classroom management and more.

The development process provided the leadership team with a mechanism for clearly thinking through what engineering-infused life and physical science instruction looks like in language that is meaningful to science teachers. Involving the pilot cohort group of teachers in a process of reviewing and refining the EIT was a significant professional development experience. In many respects, the development and refinement process represented a collaboration among the project leadership, teachers and the engineering education literature. As with many design and development projects, the process of developing and refining the tool was as important as the final product (i.e., the EIT).

Equally important was the grounding of these conversations within the literature and the NGSS. The vision of the NGSS (including the practices, crosscutting concepts and disciplinary core ideas, along with the new engineering dimension) places significant demands on teachers, curriculum developers and professional development providers. Much remains to be learned about how to reconfigure science lessons into engaging and educationally-appropriate design challenges with open-ended solutions. The challenge will be to engage students with contexts and situations where scientific knowledge is used to solve real life problems. These kinds of challenges tend to be more “messy” and complex than teaching and learning scientific facts. The challenge will be to design NGSS-based curriculum materials that will embed scientific knowledge and learning into engaging, real world contexts. To this end, the EIT was designed to extend beyond a description of engineering in science classrooms. Rather, it was designed to provide a structure for understanding the engineering dimension within the context and larger vision of the NGSS.

This material is based on work supported by the National Science Foundation Under Grant No. 1158615

References


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