Abstract

Much of the focus on K-12 engineering implies an integrative approach whereby engineering is infused into the existing curriculum, whether it is within science, technology, mathematics or other courses. However, little is yet known about how to best infuse engineering concepts into the science curriculum. Project Infuse is a collaborative project funded by the National Science Foundation that seeks to develop engineering infused science units and determine and address the associated teacher professional development needs to use them effectively. This paper outlines the approach being taken by this project and highlights the key issues involved with infusing engineering concepts into science, which include: (a) what engineering concepts are appropriate for high school science (life and physical science); (b) how these concepts can be infused into science and contribute to the learning of science content; and (c) what is the most appropriate method for assessing the learning of these concepts. These issues are discussed, along with the associated research literature and existing data from the project. It is believed that answers to these will further facilitate the infusion of engineering into the secondary level. If new science standards are to be created that include engineering concepts, it is important to specify what we want students to know and be able to do related to these concepts, how they can best be infused into the curriculum and assessed, and how teachers can be appropriately prepared to deliver them. The outcomes of Project Infuse is seeking to inform these issues.
Introduction

Much of the focus on K-12 engineering implies an integrative approach whereby engineering is infused into the existing curriculum, whether it is within science, technology, mathematics or other courses. Stand alone engineering courses are not likely to be widely implemented given the constraints of the current educational structure. At the same time, new national assessments and calls for new standards to include engineering strands, requiring new curriculum, as well as effective teacher preparation to deliver such curriculum, are emerging. For example, the National Research Council 2011 report, *A Framework for K-12 Science Standards*, includes engineering as one of four strands and identifies cross-cutting concepts in engineering, as well as science. However, little is yet know about how to best infuse engineering concepts into the science curriculum. What does it mean to infuse engineering concepts into high school science? This question raises significant issues that need to be addressed in order to effectively integrate appropriate engineering concepts to accomplish important learning outcomes.

Project Infuse is a collaborative project funded by the National Science Foundation, Discovery Research in K-12, that seeks to develop engineering infused science units and determine and address the associated teacher professional development needs to use them effectively. This project builds upon the project team’s research on engineering teacher professional development (Daugherty, 2009; Daugherty & Custer, 2010; Ross & Bayles, 2007). For example, case studies of five of the most prominent teacher professional development projects focused on engineering education were conducted leading to the finding that most lacked a clear identification of engineering learning outcomes. Teachers in the professional development were unable to explain what they were learning related to engineering apart from “the” design process. The concern is that without a clear understanding of engineering content for teachers, the connection to student learning of engineering is extremely unlikely.

In addition, the void in engineering content poses serious problems for establishing high quality engineering professional development. As has been documented in the science and mathematics teacher professional development literature, high quality professional development is rooted in rich disciplinary content (Garet, Porter, Desimone, Birman, & Yoon, 2001; Guskey, 2003; Supovitz & Turner, 2000). The National Academy of Engineering Committee on K-12 Engineering Education supported this concern of a lack of identifiable engineering content; stating that a “critical factor is whether teachers—from elementary generalists to middle school and high school specialists—understand basic engineering concepts and are comfortable engaging in, and teaching, engineering design” (Katehi, Pearson, & Feder, 2009, p. 71-72).

The Infuse Project was funded to help address this problem by developing and researching teacher learning through an innovative approach to professional development that is engineering concept-driven. The project is focused on the infusion of engineering concepts into science education (both life and physical). Leveraging key partnerships with life science (Stevens Institute of Technology) and physical science (University of Massachusetts-Boston), as well as secondary engineering education experts (Black Hills State University, Purdue University, and

---

1 This material is based upon work supported by the National Science Foundation under Grant No. 1158615. Any opinions, findings, and conclusions of recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.
University of Maryland-Baltimore County), the research team is developing an engineering concept based professional development approach and examining its viability. Specifically, the goals are:

- To understand how science teachers learn engineering concepts through a concept-based professional development program.
- To examine the implementation issues and problems encountered by teachers as they incorporate engineering concepts into standards-based curricula and instructional activities.

Although still in its pilot year, the Project Infuse research team has been engaged in foundational work that can contribute to work in this area. This has included the development and refinement of an engineering concept base, the convening of an expert panel to explore methods for infusing engineering concepts into science, and the development of an assessment instrument to measure learning gains of the concepts is in development. This paper will outline the approach being taken by this project in these endeavors and will highlight the key issues involved with infusing engineering concepts into science, which include:

(a) what engineering concepts are appropriate for high school science;
(b) how these concepts can be infused into science; and
(c) what is the most appropriate method for assessing the learning of these concepts.

**Engineering Concepts for High School Science**

In order to infuse engineering concepts into high school science, the engineering concept base must be identified, defined, and operationalized. There have been some foundational studies conducted to identify core engineering concepts for the K-12 level; however work needed to be done to further define the concepts appropriate for high school science and develop the related cognitive and performance expectations that would demonstrate understanding of the concepts. The following process was employed to define the conceptual base for engineering at a level appropriate for secondary level science education. Three stages of the process were conducted to ensure a systematic process that was rooted in the research literature and standards so that the concepts and definitions were appropriate for the secondary level: (a) identifying the concepts, (b) refining the concepts, and (c) defining the concepts.

**Stage 1: Identifying Concepts**

The primary inputs to this stage were two studies: (a) Custer, Daugherty, and Meyer (2010) and (b) Rossouw, Hacker, and de Vries (2010). The Custer, Daugherty, and Meyer (2010) study provided an in-depth analysis of a broad range of engineering-related literature and focus groups with engineering educators and engineers to identify core engineering concepts. Four types of documents were reviewed including: (a) engineering and technology philosophy writings, (b) curriculum materials focused on secondary level engineering, (c) curriculum standards documents developed for the STEM disciplines and National Academy of Engineering reports, and (d) survey research studies relevant to K-12 engineering. A series of focus groups was also conducted with 21 engineering educators and engineers. This research process resulted in a set of thirteen concepts: analysis, constraints, design, efficiency, experimentation, functionality, innovation, modeling, optimization, prototyping, systems, trade-offs, and visualization.
Rossouw, Hacker, and de Vries (2010) conducted a Delphi study and panel meeting to generate concepts and contexts that can be used for developing curricula. Three rounds were conducted. Throughout the three rounds, 32 experts were asked to generate concepts and rate each one for importance. In addition, they were provided with a draft list of concepts and definitions and asked to rate importance on a 1–5 Likert scale. From this process, the researchers narrowed the list to the following main concepts: designing (‘design as a verb’), systems, modeling, resources and values. The subconcepts were optimising, trade-offs, specifications, invention, product lifecycle, artefacts (‘design as a noun), structure, function, materials, energy, information, sustainability, innovation, risk/failure, social interaction, and technology assessment.

**Stage 2: Refining List of Concepts**

From the lists of concepts identified in the two studies, the project research team discussed the merits of each of the studies and discussed the outcomes of each. The research team decided that it would be necessary to combine and reduce the list to a manageable number of concepts for this study. A large number of concepts would make it difficult to define and assess the concepts and would also make their delivery to science teachers unnecessarily complex. The team decided to focus on a smaller set of primary concepts that are central to engineering, important at the secondary level, and can provide strong links to science education. The last criterion was informed by the National Research Council’s report, “A Framework for K-12 Science Education,” which identified cross-cutting engineering concepts important to science.

From these criteria, four primary concepts emerged and subconcepts were identified under these concepts serving to highlight key components. The concepts and subconcepts are:

- Design (constraints, tradeoffs, optimization, prototyping)
- Analysis (life-cycle, cost-benefit, risk)
- Systems (structure, functions, interrelationships)
- Modeling (visualization, prototyping, mathematical models)

**Stage 3: Defining the Concepts**

An important next step to developing the engineering concept base was to define the remaining concepts and subconcepts. A graduate student was tasked with compiling definitions of the main concepts (design, analysis, systems, and modeling) and the subconcepts (constraints, tradeoffs, optimization, prototyping, and visualization) by following a systematic process that included consulting engineering textbooks and standards documents. From these collated definitions, two members of the project leadership team read through the definitions and selected the definition that best represented the concept and should be used in the project. A decision matrix was followed in reviewing the definitions to identify the “best” definition. A definition was considered “best” if it described the concept using natural language appropriate for the secondary level. In addition, important themes and ideas represented across the definitions were noted. For example, with design, the notion of iteration was included in several of the definitions. If an existing definition did not include all of these important elements, one definition that best met them was modified to include the missing components.

Due to the project’s goal of infusing engineering into science, the definitions were compared against the definitions and/or statements about the concepts within NRC (2011) report, *A Framework for K-12 Science Education*. The framework identifies crosscutting concepts and
practices within engineering and references the four concepts throughout the document. The same graduate student collated all references to the concepts into one document and the definitions were compared against these statements. Minor modifications in wording were made to better align with the document. The table below outlines the definition selected/refined.

Table 1. Engineering Concept Definitions

<table>
<thead>
<tr>
<th>Concept</th>
<th>Definition Selected/Refined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Design is an iterative process conducted within specified constraints to develop products or systems to satisfy human needs and wants. Design typically includes components such as problem definition, data analysis, modeling, and solution refinement and has both technological and social components.</td>
</tr>
<tr>
<td>Analysis</td>
<td>Using tools such as physical, graphic and analytical models, empirical equations, and experience to analyze data and predict the performance or behavior of an object or system throughout the life of the design process.</td>
</tr>
<tr>
<td>Modeling</td>
<td>Creating a visual, mathematical, or three-dimensional representation in detail of an object or design, often smaller than the original. Modeling is often used to test and communicate ideas, make changes to a design, visualize and analyze systems, and to learn more about what would happen to a similar real object.</td>
</tr>
<tr>
<td>Systems</td>
<td>A system is a group of interrelated components designed collectively to achieve a desired goal. Systems should be studied in different contexts, including the design, troubleshooting, and operation of systems both simple and complex.</td>
</tr>
</tbody>
</table>

From these definitions, standard-type statements were generated, as well as performance expectations. Moving beyond a simple recall of the definitions, it is important that the teachers and students are able to demonstrate understanding of the concepts in ways they know and things they are able to do. These standard-type statements and performance expectations will inform the process for infusing the instruction, as well as in the development of the assessment instrument.

**Infusing Engineering Concepts into Science**

Since the goal of introducing science teachers to engineering concepts is to facilitate the learning of science content, it is important to embed the assessment of engineering concepts into science-based scenarios and content. A key premise of the project is that it is important for science teachers to develop a base level conceptual understanding of engineering in order for that understanding to facilitate the learning of science. This is opposed to simply “doing” engineering-types of activities or “hands on” projects without a grounding in conceptual level understandings. In order to inform the infusion of the engineering concepts into science instruction, a panel of 15 K-12 engineering education experts was convened to develop a model
or descriptions of effective procedures for infusing engineering concepts into instruction. In addition, the expert panel was asked to address several questions concerning concept infusion, including:

- What does it mean to infuse an engineering concept into a science lesson?
- What are the implications for infusing engineering concepts into science?
- Can engineering concepts be infused only within an engineering design lesson or can they be infused into a “typical” science lesson?

During a day-long meeting, spread over two half-days, the participants were guided through a series of discussion items to elicit elements for the creation of a model and/or descriptions of effective procedures for infusing engineering concepts into instruction. Three exemplars were presented: (a) the INSPIRES curriculum, (b) an algae farm module (developed at the Center for Innovation in Engineering and Science Education at Stevens Institute of Technology), and (c) the Active Physics curriculum. Each included a focus on engineering, and the presenters noted additional entry points for infusing engineering concepts as part of their presentations. Throughout these presentations, the expert panel reflected on the questions outlined above.

Based upon the presentations and discussions during the expert panel meeting, several conclusions were generated to help inform the Project Infuse research team’s next steps. Although a specific model was not developed, procedures or characteristics for infusing engineering concepts were identified. These characteristics were, that:

- Infusion must begin with existing science content; by identifying entry points where engineering content can be introduced in a meaningful and natural way.
- Once entry points are identified, the next step is to (a) recast the science lessons as design challenges, and (b) identify engineering-oriented challenges that deliver and reinforce the science content. Infused engineering concepts need to be taught explicitly as content, rather than simply included or mentioned in passing. Since engineering concepts are typically embedded within some form of a “design loop” model, it is important to include this information into the infusion process. Stand alone engineering concepts, abstracted from the larger engineering design process, misrepresent the integrative and robust nature of engineering.
- It appears for the effective learning of engineering concepts, a multi-week unit rather than one lesson/lab is more appropriate. However, if this much time is dedicated, the unit must also deliver on important science content learning.
- It is important that design challenges be realistic and of appropriate size and scope. If challenges are too complex and broad in scope, they may discourage rather than motivate students. Well designed engineering challenges typically include smaller, well-placed mini-challenges that are designed to build toward a more comprehensive and demanding challenge.

---

2 This expert panel meeting was funded by the National Center for Engineering and Technology Education. This material is based upon work supported by the National Science Foundation under Grant No. 0426421. Any opinions, findings, and conclusions of recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.
Design decisions within a challenge should be limited to a few options. If the context is too open-ended, students become overwhelmed by the possibilities and lose sight of the process.

When the design context requires mathematics skills and calls for the creation of artifacts, it is important that the instruction scaffold the learning and include the development of “craft skills” so they are able to implement the design challenge sufficiently.

Based upon these findings, the Project Infuse leadership team is better prepared to infuse units for science teachers and to help prepare science teachers to do the same. By refining the list of engineering concepts and developing definitions, standard-type statements, and performance expectations, the project team has a clear foundation from which to infuse into science instruction. An important aspect of infusing engineering concepts is assessment. The next section describes the project’s approach to developing an assessment of engineering concepts.

Assessing Engineering Concepts

The optimum goal for this project is to obtain an understanding of the extent to which life and physical science teachers understand the set of engineering concepts and associated sub-concepts that were identified. Thus, it is important to be able to assess teachers’ base level understanding of engineering concepts prior to and throughout the professional development process. The professional development will include a series of experiences specifically designed to enhance their understanding of the core engineering concepts (e.g., infusing engineering concepts into science curriculum modules, analysis of lessons delivered to students in science classes, engineering case study analyses). In order to accurately explore the interrelationship between engineering-oriented professional development activities, science content, and classroom learning, it is essential that the teachers’ level of understanding of engineering concepts be accurately assessed.

The research team is developing the Engineering Concept Assessment (ECA) to meet these needs. During the initial year of the five year project, the ECA is being developed and pilot tested with small cohorts of life and physical science teachers. Important inputs in the development of the ECA are the concept definitions, standard-type statements, and performance expectations and existing engineering assessment items. One of the research team members with assessment expertise is leading this effort, along with a high school teacher consult who has taught engineering for several years and has an engineering Bachelor’s degree along with his education credentials.

In the early stages of its development, several unique challenges have been identified and are being addressed that are worthy of note. These challenges include:

1. As already described, it was crucial for the research team to identify and clearly define the engineering concepts. An important aspect of this process was to develop definitions using “natural language” appropriate for science teachers at the secondary level so they can translate more easily into assessment items.

2. Given the applied nature of engineering, it is necessary to include a variety of item types on the instrument. At an understanding level, a conceptual grasp of engineering concepts can be understood through the use of multiple choice items. At a more sophisticated level, it is necessary to use scenario-based constructed response items.
3. An important aspect of the instrument is that the engineering concepts need to be contextualized within the science. More specifically, the engineering concepts will be embedded within the science content. The ECA will be specific to engineering infused within science.

4. A yet to be resolved issues is the extent to which the ECA can be used with science teachers and secondary level science students. Pilot and field testing will be conducted to examine this feature of the instrument. The assumption is that since engineering concepts are relatively new to both teachers and secondary level students and given the emphasis on the use of “natural language” that an instrument can be designed that will work for both teachers and students.

It is believed that this work will facilitate students’ learning of science through the infusion of engineering concepts and activities. If new science standards are to include engineering concepts, it is important to specify what we want students to know and be able to do, how they can best be infused into the curriculum and assessed, and how teachers can be appropriately prepared to deliver them. Project Infuse is seeking to inform these important issues.

References