Teaching the Nature of Engineering in K-12 Science Education: A Delphi Study (Fundamental)

Dr. Brian Hartman, Walla Walla University

Brian is a professor of education at Walla Walla University. He has 5 years of experience teaching high school science and practiced engineering for 12 years. His research interests include K-12 biological and chemical engineering curriculum development, nature of engineering, and creativity in engineering design.

Randy L. Bell, Oregon State University

Dr. Bell is an Associate Dean and Professor of Science Education in the College of Education at Oregon State University. His science background includes degrees in Botany and Forest Ecology. Dr. Bell’s interest in sharing science with others led him to earn a teaching license and then teach science for six years in a rural high school in Eastern Oregon, where he was recognized as the Oregon Science Teachers Association’s "New Science Teacher of the Year." Eventually, Dr. Bell’s interest in educational research and science teacher preparation led him back to graduate school, where he earned the PhD in Science Education in 1999. For the past 16 years, Dr. Bell has been heavily involved in teaching preservice teachers, providing professional development for practicing teachers, and research and development related to teaching and learning about the nature of science and scientific inquiry. Dr. Bell also conducts research and develops resources for integrating technology into science teaching. Dr. Bell has maintained strong ties to public schools through a variety of collaborative projects. Most recently, he completed a 28 million-dollar US DOE-funded I3 project designed to provide research-based professional development to Virginia’s elementary and secondary science teachers. The author of more than 170 articles, chapters and books, Randy currently serves as Associate Dean of Academics and Professor of Science Education in the College of Education at Oregon State University.
Teaching the Nature of Engineering in K-12 Science Education

by

Brian D. Hartman, Randy L. Bell, and Larry Flick
Introduction

Engineering has been increasingly promoted in K-12 science education through national and state standards. Arguments for including engineering in K-12 science include improving science and mathematics learning, increased engineering awareness, experience with design, increasing interest in engineering as a career, and increased technological literacy (National Academy of Engineering & National Research Council, 2009). The National Research Council (NRC) has now extended this position by including engineering practices on the same level as science practices in the Next Generation Science Standards (NGSS Lead States, 2013).

Including engineering in science standards poses a unique challenge for the field of science education. Engineering is a broad field and it not yet clear which engineering “core ideas” will best leverage student knowledge of STEM (science, technology, engineering, and mathematics) disciplines (Moore, Tank, Glancy, and Kersten, 2015). K-12 engineering, like science can be seen a containing three domains: A body of knowledge, a set of practices or methods, a way of knowing or the nature of engineering (Pleasants, Spinler, & Olson, 2016; Spector & Lederman, 1990). Of the three domains, the nature of engineering is the only one that attempts to answer questions about what engineering is as a discipline. By developing a better understanding of engineering as a way of knowing, we may be able to gain a better understanding of how to integrate engineering into traditional academic courses such as mathematics and science. Understanding the nature of engineering (how it arrives at knowledge, its history, and its
social practices) would provide a solid foundation for answering questions about the potential place of engineering in K-12 curriculum. This investigation addresses the need for improved understanding of engineering by investigating aspects of the nature of engineering as they apply to K-12 education.

In 2013, the Next Generation Science Standards reflected the growing interest in K-12 engineering by integrating it with the science curriculum. In contrast to the prior standards, the NGSS explicitly included engineering as a foundational component of the curriculum, with engineering concepts included in the requirements for each grade level. In fact, the final NGSS document body included over three hundred uses of the word engineering. Taking advantage of recent research into science learning, the standards also propose a new view of teaching science. Whereas the earlier standards heavily emphasized science content knowledge, the new standards took a more holistic view of science. Science education, under the new perspective, was proposed as enacting a set of scientific and engineering practices. Scientific knowledge is therefore integrated with the practices for its use. What is unique about the NGSS practices is that both science and engineering have equal priority in the framework. This is a large change for national science standards in the United States. While engineering design has been a component of technology education standards for some time, these standards do not address engineering in a comprehensive way (International Technology Education Association, 2007). Engineering is a new concept for many science teachers who have been trained in traditional ways of teaching science. Teachers will need to develop a robust
NATURE OF ENGINEERING FOR K-12 EDUCATION

understanding of the field engineering if they are to make these significant changes to their teaching practice.

While the NGSS emphasize design as the primary activity of engineering (NGSS Lead States, 2013) it also makes it clear that engineering is more broad than this concept alone. Many have argued that engineering is a multi-faceted activity that cannot be encompassed by design alone (Dias, 2013; Figueiredo, 2008; Vincenti, 1990). These authors argue that students need to understand the multi-faceted nature of engineering to understand the field. Others in the engineering education field have similarly made the case that teaching only design in K-12 engineering education will leave students with an incomplete view of engineering (Moore, Tank, Glancy, & Kersten, 2015; Carr, Bennett, & Strobel, 2012). Science education researchers have argued that it is important for students to understand of the nature of science because it expands student understanding beyond scientific inquiry, the primary activity of science (Bartos, Lederman, 2014). In a similar approach, K-12 students should also understand the nature of engineering, not just engineering design (the primary activity of engineering). A better understanding of the nature of engineering would provide a foundation for students to better understand engineering.

Literature

Although research into the nature of engineering for K-12 audiences currently has little published literature, research into the nature of science has a longer history. In a recent analysis of the key literature published since 1990 in the field of science education Chang, Chang, and Tseng (2010) identified the topic ‘nature of science’ as one of the
nine major topics of the field. In 1990, the authors located only two articles on the topic of the nature of science. By 2007, the number had grown to 191 papers. As of 2007 (the last year of analysis) the nature of science had grown to become the second-most published topic in the field. Only publications on conceptual change exceeded the publication rate of the nature of science. The growth of publications on the topic of the nature of science in K-12 education highlights value of this line of research to the science education community.

While a large volume of work has been completed on the nature of science, only a limited amount of research has been conducted on the nature of engineering. Karatas, Bodner, and Unal (2015) reported an investigation that evaluated the views of first-year engineering students on the nature of engineering. The paper provides an insight into university student conceptions of engineering as well as describing aspects of the nature of engineering. The Karatas, et al. (2015) peer-reviewed paper appears to be based on an unpublished thesis by Karatas (2009). The author identifies the nature of science as an area that has seen a large quantity of research in the field. Karatas (2009) notes that the nature of engineering has not seen the development of a list of tenets similar to the nature of science. Karatas (2009) developed a list of tenets of the nature of engineering that he believed were appropriate for post-secondary research. He states that these tenets were “...Derived from several sources and demonstrated my view of the nature of engineering” (Karatas, 2009, p. 32). The list of tenets for the nature of engineering that he developed are “Goal-orientated design”, “Tentative/Temporary”, “Theory, artifact, and failure-laden”, “Social and cultural”, “The method”, “Creativity, imagination, and
NATURE OF ENGINEERING FOR K-12 EDUCATION

integration”, “Decision making”, “Holistic” (Karatas, 2009, p. 33-41). Karatas (2009) goes on to provide literature citations for each tenet. This view of the nature of engineering is the first known attempt to identify specific aspects of engineering as a way of knowing.

Using the above list of tenets of the nature of engineering, Karatas (2009) developed a Views of the Nature of Engineering (VNOE) survey to be used with first-year engineering students enrolled at a Midwestern public university. He selected 114 students to take the instrument and 20 additional first-year students to participate in interviews the following year. Karatas (2009) developed the VNOE survey by creating questions that addressed various aspects of the nature of engineering described above. The interrelated aspects of the nature of engineering were: Definition of engineering, purposes of engineering, the difference between engineering and science, the nature of engineering, and reasons for choosing engineering as a career. The questions used in the survey were based on a pilot investigation (45 students) and face-to-face interviews with three students. After administering the instrument, Karatas (2009) coded the responses using inductive data analysis. After analysis, Karatas (2009) found that the first-year students viewed engineering as problem solving (57%), applications of science (29%), creating solutions (31%), designing real-world products (22%), and discovering how things work (8%). Among other responses, they viewed engineering as working under constraints (86%) and developing specifications (67%). These responses indicate a relatively narrow view of the nature of engineering by first-year students as compared to that proposed by national organizations. Given that the students were recently in high
school, this investigation points to the need to improve the understanding of K-12 students so they can better know the careers they are choosing.

Methods

The methodology employed for this research was the three-round Delphi investigation first described by Helmer and Rescher (1959). The Delphi technique is a semi-structured mixed methods approach that consists of one qualitative round followed by two or more quantitative rounds. The Delphi technique aims to improve consensus development within a group of experts by reducing issues associated with face-to-face group methods such as the traditional committee meeting and nominal group technique. The key characteristics of a Delphi investigation that aim to reduce the issues of face-to-face consensus meetings are: Anonymity of participant responses, multiple rounds, researcher-controlled feedback to participants, and statistical results of group responses (Rowe & Wright, 1999). This investigation utilized a three-round Delphi because it has been be used extensively in curriculum studies (Osborne, et al., 2003; Bolte, 2008; Kloser, 2014). The three-round Delphi investigation has typically been used for curriculum framework studies because it develops a consensus in a reasonable amount of time and also reports importance of items. Given the relatively new field of K-12 engineering education, the Delphi methodology was chosen because it is characterized as developing useful curriculum without the existence of prior frameworks.

The Delphi method has some advantages over other techniques that might be employed in a curriculum investigation. Because the technique does not require face-to-face contact, expert groups can be surveyed that would be unable to meet together
In addition, the consensus of a group can be obtained even if the personality styles of the participants might hamper a face-to-face meeting. Because the Delphi method utilizes written communication, responses are more likely to be reasoned and thoughtful because the participants have time to compose their responses (Akins, Tolsen, & Cole, 2005). Written communication also allows researchers to capture a record of the communication between participants for further analysis. These advantages make the Delphi technique an ideal methodology for use in a curriculum investigation.

Initial Invitation

Participants were recruited from the following categories: K-12 science teachers, K-12 engineering/technology teachers, university science education professors and university engineering education professors. The goal was to recruit similar proportions from each group with a total of 30 participants completing all rounds of the study. Potential candidates were identified through their involvement professional associations. K-12 engineering teachers were invited based on their membership in the International Technology and Engineering Education Association (ITEEA). K-12 science teachers were invited based on making a presentation at either state, regional, or national meetings of the National Science Teacher Association (NSTA). University engineering education professors were recruited based on being a member of either the precollege engineering education group or the engineering literacy / philosophy of engineering division of the American Society of Engineering Education. University science educators were recruited based on their membership in the National Association for Research in Science Teaching.
The initial invitation (See Appendix A) was sent to association mailing lists that included individuals with the potential of being qualified for the study.

Due to the overwhelming response rate (428 qualified participants) participants were randomly selected to participate in the Delphi investigation. In order to ensure participants have an understanding of K-12 engineering education, only respondents that have appropriate background education, are involved in K-12 engineering teaching or research, and use K-12 engineering concepts in classes that they teach were included in the potential participant pool. From this pool, 25 participants were randomly selected from each of the four categories described above yielding a total of 100 participants who were sent the Round 1 questionnaire (See Table 5).

Round 1

The first step of the research project was to send a single question to the 100 randomly selected participants from the 428 qualified respondents. Participants were asked to, “Please list all the characteristics of the nature of engineering that are important for K-12 students to know. “ Participants were asked to respond with a list of ideas they believed were important for K-12 education. In addition, they were asked to provide a description for each characteristic and explain the items in greater detail. Participants were not given a limit to the number of items they could list. This open-ended question provided an opportunity to participants to generate an exhaustive list of characteristics of the nature of engineering with minimum direction, reducing bias.

The Round 1 questionnaire was sent in November 2015 using the Qualtrics Online Survey Software (2016) and participants were given two weeks to respond.
NATURE OF ENGINEERING FOR K-12 EDUCATION

Reminders were sent one week and one day before the questionnaire close date. A total of 64 participants responded with a total of 499 ideas. In order to develop a list of nature of engineering themes from the participant responses, each item to was coded using the open-coding technique recommended by Glaser and Strauss (1967). Open coding is the first step of the Grounded Theory methodology and involves naming and categorizing each line of text. Each sentence was evaluated for concepts related to the nature of engineering and labeled. A first round of coding was completed with a second researcher using the Nvivo (2015) software. One-third of the ideas were initially coded with the second researcher to develop a codebook that could be applied to the remaining responses. The primary researcher then coded all of the remaining items using the codebook developed. The second researcher then reviewed coded items and any conflicted items were reviewed until both coders agreed. After coding was completed, 19 themes remained. Each theme was given a title and a summary sentence to be used in subsequent rounds. Table 6 shows each theme along with ratings developed in Round 2 and 3 of the process. The coding process was designed to minimize researcher bias and allow participants to set the course of the investigation.

Round 2

The Round 2 questionnaire gave participants the opportunity to review the themes developed from Round 1 and to rate each theme on a five-point Likert-type scale (1= Not Important, 2= Slightly Important, 3= Moderately Important, 4= Important, and 5= Very Important). The Round 2 questionnaire was sent to participants in November 2016 and participants were given two weeks to submit their results. Reminders were sent both one
NATURE OF ENGINEERING FOR K-12 EDUCATION

The participants were asked to evaluate each item for it important to a K-12 curriculum. Participants were able to justify the rating they gave so that their thinking could be disseminated to the other members of the panel in Round 3. The participants were also given the opportunity to add additional items they believed were missing from the Round 2 theme list. The goal of Round 2 was to give participants the opportunity to narrow down the theme list so that only the most important items were taken to the next questionnaire.

Of the 64 participants that completed Round 1, 63 completed Round 2. Participants were given two weeks to complete the survey with reminders sent one week and one day prior to the close date. The mean, mode, standard deviation and percent of participants rating an item as a 4 or above (important or very important) were calculated for each item. Individual comments were collated from each item and a representative set of responses was created to communicate the thinking of the panel. Of the 19 themes identified in Round 1, 14 had a rating >= 4 (Important) and 13 had standard deviations that were lower than 1.0. This indicated that a majority of the questions had some degree of consensus from the outset.

Round 3

The final questionnaire was developed from both the quantitative and qualitative responses to Round 2. The comments on each item from Round 2 were reviewed and slight wording changes were made to clarify the item in light of participant suggestions. The Round 3 questionnaire consisted of the revised title and description for each theme along with mean, standard deviation, and percent rating greater than or equal to 4.
Based on comments from participants, two themes were combined: The User Focused theme was merged into the Contextual theme.

Representative comments on each item were provided to the participant to communicate the thoughts made by participants in Round 2 (See Figure 1). Participants were asked to rate the item again for importance (1=not important to 5=important) and provide a justification if their rating was more than 1 point from the mean from Round 2. In addition, participants were given the opportunity to make comments about each item. Since each item had three questions (rating, justification, and comments) the total survey would have been 54 questions long. Concerns for participant fatigue and quality responses led the author to reduce the number of items on the survey to those with the highest ratings. Only items with a mean $\geq 4$ (important or very important) and / or items with a mode of 5 were used in Round 3 (as per Osborne, et al., 2003). The themes not taken into Round 3 were: Accessible to Everyone, Unique Disciplines, and Historical.

The Round 3 questionnaire was sent to participants in January 2016 and participants were given two weeks to submit their results. Reminders were sent both one week and one day prior to the close date. A total of 61 participants completed the questionnaire giving a final response rate of 61% of participants completing all three rounds. Mean, mode, standard deviation, and percent rating greater than 4 (important or very important) were calculated for each item. These values were used to guide final decisions about which items were retained in the final list of themes.
Researchers using the Delphi method have defined consensus and stability in many ways. There does not appear to be agreement on the best methodology to use in either of these cases (Giannarou & Zervas, 2014; Osborne, 2003; Walker & Selfie, 2015) so it is up to the researcher to choose among approaches and cutoff-off levels. As mentioned earlier, consensus represents the level of unity among ratings and stability represents the consistency of ratings of a theme from Round 2 to Round 3. For this investigation, consensus was defined as minimum of 75% of participants rating a theme at 4 or greater (important or very important) in Round 3 (as per Christie & Barela, 2005; Tigelaar, Dolmans, Wolfhagen, & van der Vleuten, 2016). Stability was defined as a distribution change of less than 15% between Round 2 and Round 3 as defined by Scheibe, Skutsh, & Schofer (2002). While some researchers have used the change between rounds as the measure of stability (Von der Gracht, 2012), it is possible for significant changes to occur in ratings and still yield the same results (i.e. high ratings drop and lower ratings rise showing the same average change. This leaves the possibility that themes would appear to be stable when in-fact large changes have occurred between rounds. The final results presented in this investigation are the themes achieved both stability and consensus between Round 2 and Round 3. It is not known whether additional rounds would have increased the number of items achieving stability, but the number of rounds were limited to three in advance to reduce participant fatigue.

From this analysis, eight themes met the requirements of being both stable and achieving consensus. The themes (shown in Table 6) include: *Multiple Solutions*, *Creative, Learns from Failure, Uses Modeling, Requires Communication, Criteria and*
Constraints, Collaborative, and Unique Way of Knowing. Most of the themes in Round 3 showed high levels of consensus (greater than 85% rating 4 or above) except for the themes: Problem Focused and Develops Products, Processes, and Protocols (with 67% and 73% rating above 4, respectively). Of the themes with high consensus, the most stable were Multiple Solutions, Creative, Learns from Failure, and Requires Communication, and Unique Way of Knowing (with 10% or greater stability). The themes, Uses Modeling, Criteria and Constraints, and Collaborative were less stable but had stability between 15% and 11%. The remaining items (Involves Systems Thinking, Design Process, Multidisciplinary, Ethical, and Contextual) had the least stable results with values ranging from 16% to 23%.

While some items were not included on the final list due to low consensus or lack of stability, the final list does appear to represent a comprehensive view of the nature of engineering. Themes such as Design Process, Problem Focused and Ethical may have not achieved consensus and stability due to comments made by participants in Round 2 (see comments above). Other themes may have had less support from the beginning. For example, the theme Involves Systems Thinking, only had five comments, which is far fewer than other themes. Other themes, such as Multidisciplinary and Contextual had showed consensus (greater than 75% rating as important or very important), but were below the line for stability (15% change in distribution between Round 2 and Round 3). While it is possible that some of these themes would have increased in stability if another survey round had been completed as part of the planned survey protocol, a total of eight items in the final list is a reasonable length.
NATURE OF ENGINEERING FOR K-12 EDUCATION

Group Differences

In order to understand differences between group ratings, the results of the final list of themes were analyzed by type of participant category (K-12 engineering teacher, K-12 science teacher, university engineering education professor, and university science education professor). Because the participants were purposively sampled from experts in the field and were not intended to be a representative sample of their subgroup, inferential statistics were not performed. Although some Delphi studies do include between group comparisons such as ANOVA (Osborne, 2002) it is not clear what population the authors of these studies is inferring to. In the present case, each group was a reasonable size (starting with 25 participants each) so descriptive comparisons utilizing mean would be useful in understanding subgroup responses (see Table 7).

It is clear from this analysis that most subgroups had similar ratings. All subgroups except for K-12 science teachers had average ratings within 0.10 of the overall mean. K-12 science teachers, however, rated their themes 0.20 less than the overall average. When looking at individual themes, this result doesn’t appear to be due to one or two themes being rated lower. Seven of the eight final themes were rated lower than the overall mean by the K-12 science teacher subgroup. For example, the theme Criteria and Constraints was rated 0.47 lower than the overall average for that theme. The only theme that was rated higher than the overall average was the Creative theme. K-12 science teachers rated this item 0.32 higher than the overall average. For other groups, the majority of the themes were rated closely to the overall mean with a few exceptions. K-12 engineering teachers rated the Design Process theme 0.29 higher than the mean.
NATURE OF ENGINEERING FOR K-12 EDUCATION

Engineering education professors rated the *Unique Way of Knowing* theme 0.21 higher than the overall average for that theme. The *Design Process* theme showed varied results across subgroups. The engineering-oriented subgroups both rated this theme higher than average (0.27 for K-12 teachers and 0.33 for university professors). The science-oriented subgroups both rated the *Design Process* theme lower than the average (0.26 lower for K-12 teachers and 0.34 lower for university professors). Based on the comments from the science-oriented subgroups, there may have been a fear that the engineering design process has the potential to become a standardized process in which all students are taught the same steps. It is possible this is why the science-oriented subgroups rated this theme lower than the engineering-oriented subgroups. It is interesting to note that even if the science-oriented subgroups were eliminated from the analysis, the *Design Process* theme would still not have met the criteria for stability.

When completing the analysis on the engineering-oriented subgroups only, the rating would have been 4.74 (on a five-point scale) but the theme showed a change in rating by 19% of the respondents (above the 15% cutoff level used for stability in this investigation). This would have led to the *Design Process* theme not being included in the final theme list. Evaluating the subgroups gives some understanding to the mean ratings seen in Table 6. While the consensus of the entire group was the goal of this investigation, it is valuable to see subgroup perspectives on individual items.

**Conclusions**

To date, the field of engineering education has not seen efforts to develop a consensus regarding what aspects of the nature of engineering are appropriate for K-12
education. While researchers did develop a list of tenets of engineering for use at the university level (Karatas, Bodner, & Unal, 2015), this list was developed by reviewing the literature rather than by empirical methods. A comprehensive, empirically based consensus on the nature of engineering for K-12 students would further engineering education by guiding policy, supporting curriculum development, and helping classroom teachers to focus on the important aspects of the field.

While there are potentially a large number of individual themes that could be considered appropriate for K-12 education, the goal of this research was to find themes that could be agreed upon by stakeholders in the field: K-12 teachers and professors in science and engineering education. Indeed, a total of 19 themes were suggested during Round 1 for potential inclusion in the list. While it is not likely that a consensus would be developed on this set of themes, agreement on a small subset of themes was the goal of the project. Based on the results of three rounds of surveys sent to the 100 participants on the panel, there does appear to be evidence of a consensus with stability for eight themes. While additional themes could be included in such a list, these results provide empirical support for a core of ideas about engineering that would be suitable for inclusion in the K-12 curriculum. Using the Delphi methodology, the evidence for consensus includes high ratings of importance by a large majority of participants, low variability in ratings (standard deviation, and small number of participants changing their answers between rounds. These results provide a starting point from which further research can launched to expand and validate these findings.
NATURE OF ENGINEERING FOR K-12 EDUCATION

A concern in identifying a collection of items important to the nature of engineering in K-12 education is that these themes may be taught as an isolated list separated from their meaning. Other researchers have identified this potential issue in science education (Osborne, 2003; Hodson, 2009) and is relevant given the didactic use of the six-step scientific method in K-12 education of the past (Bauer, 1994). It is important to note that the themes identified in this investigation are not intended to a definitive list of aspects of the nature of engineering. A number of participants commented on the inter-relatedness of themes and the potential for adding additional themes. Michael Matthews (2011) argues that the nature of science could be increased to 15 or 20 tenets that would expand views of the nature of science. The same argument could be made for the nature of engineering. The Delphi methodology (as implemented in this investigation) is qualitative at its core. The 4,281 participants invited to the investigation, while representing many regions of the United States, was not intended to be a randomized sample of engineering and science educators. As with other qualitative methods, the researcher background and perspectives are the foundation of the theme generation process. Even the numeric aspects of the Delphi process are descriptive in nature and do not represent statistically significant differences that can be inferred to the larger population. The goal of this investigation is to provide a starting point for future research that could expand and clarifies the themes that were developed. It is hoped that this understanding will temper the urge to implement the list of eight themes developed in this investigation as a list of items to be memorized by students.
NATURE OF ENGINEERING FOR K-12 EDUCATION

It is also important to note that the cut-off points for both consensus and stability were chosen based on the work of prior researchers. This investigation defined consensus as having a minimum of 75% of participants rating a theme as important or very important. In addition, stability was defined as less than a 15% change in distribution between Round 2 and Round 3. A number of items met the consensus requirement, but not the stability requirement by Round 3. These items include *Involves Systems Thinking* (4.50 rating on a 5 point scale), *Design Process* (4.43 rating), *Multidisciplinary* (4.42 rating), *Ethical* (4.30 rating), and *Contextual* (4.25 rating). With additional rounds or a different group of participants, these concepts might have been included in the final list of themes. The final list, therefore, represents only the highest priority items that could be included in K-12 education. Additional items could be included depending on the level of detail required.
Table 4

*Expert Selection Criteria for Delphi Investigation*  

<table>
<thead>
<tr>
<th>Criterion</th>
<th>K-12 Teachers</th>
<th>University Professor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Education</td>
<td>Professional development in engineering education</td>
<td>PhD in science, science education, engineering, or engineering education</td>
</tr>
<tr>
<td>Teaching / research background</td>
<td>Taught three or more years</td>
<td>Research in K-12 engineering</td>
</tr>
<tr>
<td>K-12 Engineering in practice</td>
<td>Includes engineering concepts in classes taught</td>
<td>--Or--</td>
</tr>
<tr>
<td>K-12 Engineering in practice</td>
<td>Includes engineering concepts in classes taught</td>
<td>Includes K-12 engineering in courses taught</td>
</tr>
</tbody>
</table>

Table 5

*Participants Completing Each Delphi Round by Group.*

<table>
<thead>
<tr>
<th>Group</th>
<th>Responded</th>
<th>Qualified</th>
<th>Selected</th>
<th>Round 1</th>
<th>Round 2</th>
<th>Round 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-12 Engineering Teachers</td>
<td>125</td>
<td>112</td>
<td>25</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>K-12 Science Teachers</td>
<td>178</td>
<td>121</td>
<td>25</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>University Engineering Education Professor</td>
<td>136</td>
<td>99</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>24</td>
</tr>
<tr>
<td>University Science Education Professor</td>
<td>171</td>
<td>96</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>Totals</td>
<td>610</td>
<td>428</td>
<td>100</td>
<td>64</td>
<td>63</td>
<td>60</td>
</tr>
</tbody>
</table>
Table 6

**Themes and Ratings from Round 2 and Round 3**

<table>
<thead>
<tr>
<th>Theme and Summary Statement</th>
<th>Round 2</th>
<th></th>
<th></th>
<th></th>
<th>Round 3</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Mode</td>
<td>SD</td>
<td>%&gt;4</td>
<td>Mean</td>
<td>SD</td>
<td>%&gt;4</td>
<td>Stability</td>
</tr>
<tr>
<td><strong>Multiple Solutions</strong></td>
<td>4.52</td>
<td>5</td>
<td>0.74</td>
<td>89%</td>
<td>4.70</td>
<td>0.46</td>
<td>100%</td>
<td>9%</td>
</tr>
<tr>
<td><strong>Creative</strong></td>
<td>4.40</td>
<td>5</td>
<td>0.75</td>
<td>90%</td>
<td>4.52</td>
<td>0.68</td>
<td>93%</td>
<td>8%</td>
</tr>
<tr>
<td><strong>Learns from Failure</strong></td>
<td>4.38</td>
<td>5</td>
<td>0.81</td>
<td>83%</td>
<td>4.52</td>
<td>0.70</td>
<td>92%</td>
<td>8%</td>
</tr>
<tr>
<td><strong>Uses Modeling</strong></td>
<td>4.37</td>
<td>5</td>
<td>0.79</td>
<td>84%</td>
<td>4.52</td>
<td>0.62</td>
<td>97%</td>
<td>12%</td>
</tr>
<tr>
<td><strong>Involves Systems Thinking</strong></td>
<td>4.37</td>
<td>5</td>
<td>0.77</td>
<td>83%</td>
<td>4.50</td>
<td>0.54</td>
<td>98%</td>
<td>19%</td>
</tr>
<tr>
<td><strong>Requires Communication</strong></td>
<td>4.46</td>
<td>5</td>
<td>0.71</td>
<td>90%</td>
<td>4.47</td>
<td>0.62</td>
<td>93%</td>
<td>8%</td>
</tr>
<tr>
<td><strong>Criteria and Constraints</strong></td>
<td>4.52</td>
<td>5</td>
<td>0.67</td>
<td>94%</td>
<td>4.45</td>
<td>0.70</td>
<td>95%</td>
<td>11%</td>
</tr>
<tr>
<td><strong>Design Process</strong></td>
<td>4.54</td>
<td>5</td>
<td>0.78</td>
<td>89%</td>
<td>4.43</td>
<td>0.74</td>
<td>93%</td>
<td>23%</td>
</tr>
<tr>
<td><strong>Multidisciplinary</strong></td>
<td>3.79</td>
<td>4</td>
<td>1.02</td>
<td>65%</td>
<td>4.42</td>
<td>0.77</td>
<td>92%</td>
<td>16%</td>
</tr>
<tr>
<td><strong>Collaborative</strong></td>
<td>4.52</td>
<td>5</td>
<td>0.64</td>
<td>95%</td>
<td>4.40</td>
<td>0.72</td>
<td>87%</td>
<td>13%</td>
</tr>
<tr>
<td><strong>Ethical</strong></td>
<td>4.38</td>
<td>5</td>
<td>0.77</td>
<td>83%</td>
<td>4.30</td>
<td>0.74</td>
<td>87%</td>
<td>17%</td>
</tr>
<tr>
<td><strong>Unique Way of Knowing</strong></td>
<td>4.02</td>
<td>5</td>
<td>1.01</td>
<td>75%</td>
<td>4.27</td>
<td>0.76</td>
<td>85%</td>
<td>10%</td>
</tr>
<tr>
<td><strong>Contextual</strong></td>
<td>4.05</td>
<td>4</td>
<td>0.87</td>
<td>76%</td>
<td>4.25</td>
<td>0.57</td>
<td>93%</td>
<td>19%</td>
</tr>
<tr>
<td><strong>Develops Products, Processes, Protocols</strong></td>
<td>3.92</td>
<td>5</td>
<td>1.07</td>
<td>68%</td>
<td>3.87</td>
<td>0.72</td>
<td>73%</td>
<td>34%</td>
</tr>
<tr>
<td><strong>Problem Focused</strong></td>
<td>4.62</td>
<td>5</td>
<td>0.58</td>
<td>95%</td>
<td>3.80</td>
<td>1.07</td>
<td>67%</td>
<td>31%</td>
</tr>
<tr>
<td><strong>Unique Disciplines</strong></td>
<td>3.79</td>
<td>4</td>
<td>1.02</td>
<td>65%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Accessible to Everyone</strong></td>
<td>3.79</td>
<td>4</td>
<td>1.08</td>
<td>63%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Historical</strong></td>
<td>3.32</td>
<td>3</td>
<td>1.04</td>
<td>38%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Note: Items rated from 1=not important to 5=very important*
## Table 7

*Comparison of Round 3 Results for each Group (N=60)*

<table>
<thead>
<tr>
<th>Theme</th>
<th>K-12 Engineering</th>
<th>K-12 Science</th>
<th>University Engineering</th>
<th>University Science</th>
<th>Combined Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple Solutions</td>
<td>4.57</td>
<td>4.50</td>
<td>4.71</td>
<td>4.78</td>
<td>4.70</td>
</tr>
<tr>
<td>Creative</td>
<td>4.57</td>
<td>4.83</td>
<td>4.38</td>
<td>4.83</td>
<td>4.52</td>
</tr>
<tr>
<td>Learns from Failure</td>
<td>4.43</td>
<td>4.83</td>
<td>4.46</td>
<td>4.52</td>
<td>4.52</td>
</tr>
<tr>
<td>Uses Modeling</td>
<td>4.57</td>
<td>4.50</td>
<td>4.38</td>
<td>4.65</td>
<td>4.52</td>
</tr>
<tr>
<td>Requires Communication</td>
<td>4.57</td>
<td>4.00</td>
<td>4.63</td>
<td>4.39</td>
<td>4.47</td>
</tr>
<tr>
<td>Criteria and Constraints</td>
<td>4.43</td>
<td>4.00</td>
<td>4.38</td>
<td>4.65</td>
<td>4.45</td>
</tr>
<tr>
<td>Collaborative</td>
<td>4.43</td>
<td>4.17</td>
<td>4.50</td>
<td>4.35</td>
<td>4.40</td>
</tr>
<tr>
<td>Unique Way of Knowing</td>
<td>4.29</td>
<td>4.00</td>
<td>4.13</td>
<td>4.48</td>
<td>4.27</td>
</tr>
<tr>
<td>Mean</td>
<td>4.52</td>
<td>4.27</td>
<td>4.51</td>
<td>4.47</td>
<td>4.47</td>
</tr>
<tr>
<td>Difference from overall Mean</td>
<td>0.09</td>
<td>-.20</td>
<td>0.04</td>
<td>0.00</td>
<td>4.48</td>
</tr>
</tbody>
</table>
Table 8

*Comparison of Approaches to the Nature of Engineering*

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple Solutions</td>
<td></td>
<td>Tentative / Temporary</td>
<td>Iterative</td>
<td>Many Solutions, tradeoffs</td>
</tr>
<tr>
<td>Creative</td>
<td></td>
<td>Creativity, imagination, and integration</td>
<td>Creative</td>
<td>Require creativity</td>
</tr>
<tr>
<td>Learns from Failure</td>
<td></td>
<td>Theory, Artifact, and Failure Laden</td>
<td></td>
<td>Iterative</td>
</tr>
<tr>
<td>Uses Modeling</td>
<td></td>
<td></td>
<td>Models</td>
<td></td>
</tr>
<tr>
<td>Requires Communication</td>
<td></td>
<td></td>
<td>Reasoning from evidence</td>
<td></td>
</tr>
<tr>
<td>Criteria and Constraints</td>
<td></td>
<td>Decision making</td>
<td>Design with constraints</td>
<td>Works under constraints</td>
</tr>
<tr>
<td>Collaborative</td>
<td></td>
<td>Social and cultural</td>
<td>Collaborative</td>
<td></td>
</tr>
<tr>
<td>Unique Way of Knowing</td>
<td>Goal-oriented design</td>
<td></td>
<td></td>
<td>Technical Design</td>
</tr>
<tr>
<td></td>
<td>Social and cultural</td>
<td></td>
<td></td>
<td>Stakeholder needs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Problem Solving</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Theory and practice</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Holistic</td>
<td>Systems thinking</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Systems thinking</td>
</tr>
</tbody>
</table>
NATURE OF ENGINEERING FOR K-12 EDUCATION

Figure 1

*Example Survey Item from Round 2 and Round 3 Surveys.*

<table>
<thead>
<tr>
<th>Problem Focused</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concept:</strong> The goal of engineering is to solve problems that meet perceived needs and wants. Engineers often work in organizations that assign projects they believe can be sold to a customer and will generate a profit.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean:</strong> 4.62</td>
</tr>
<tr>
<td><strong>Standard Deviation:</strong> 0.58</td>
</tr>
</tbody>
</table>

95% of panelists rated 4.00 or above (Important or very important)

<table>
<thead>
<tr>
<th>Summary of comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>• One respondent does not agree with the word &quot;perceived&quot; in the theme statement.</td>
</tr>
<tr>
<td>• The idea that engineering is to improve the quality of life for people should be included.</td>
</tr>
<tr>
<td>• This statement paints a falsely positive view of engineering as working toward the public good. Most engineering is conducted with a profit motive. Engineering addresses real needs as well as a false sense of need. An educated citizen should be able to identify the difference between needs and wants.</td>
</tr>
</tbody>
</table>
Implications

The nature of engineering themes developed in this research investigation have some overlap with prior efforts to define aspects of the nature of engineering. The results of this investigation (see table 8) align most closely with the list nature of engineering tenets developed from the literature by Karatas (2009). His investigation includes five aspects of the nature of engineering identified in this investigation except *Uses Modeling*, *Requires Communications* and a *Unique Way of Knowing*. The authors of the NGSS Framework for K-12 Science Education (NRC, 2009) also identified six aspects of the nature of engineering that overlap with the final list of themes for this investigation. The only themes that do not overlap are *Collaborative*, and a *Unique Way of Knowing*. There is an overlap of four themes with the ASEE engineering teacher’s standards (ASEE, 2014a) nature of engineering concepts deemed important from a literature search. The themes that do not overlap are *Requires Communication*, *Collaborative*, and *Unique Way of Knowing*. The one nature of engineering concept that was not identified in this investigation but was included all three literature-search based studies was the *Design Process* theme.

As detailed earlier, the *Design Process* theme stimulated a robust debate among participants. Some participants (including a large number of K-12 engineering teachers and professors) felt that the engineering design process was an important part of the nature of engineering for students. They viewed the engineering process as a simple way to communicate engineering to K-12 students. They believed that
students should be able to internalize the steps of the process so they could know what
to do next in engineering activities. On the other side of the debate, some participants
(including a large number of K-12 science teachers and professors) were worried that
the design process would be turned into a linear set of steps that students would
memorize. Some participants saw the engineering process as non-linear, and intuitive
rather than structured. While this theme showed consensus (with a 4.43 rating), a large
number participants (23%) changed their ratings between Round 2 and Round 3. It is
possible that concept of technical design without a structured process might have
shown more support from participants, but this was not indicated from participant
comments. In the end, over half of the themes identified in this investigation were
included in three other major efforts to clarify the nature of engineering. This large
overlap provides indicates that the concepts developed in this investigation are largely
in line with other literature-review based studies. The empirical results of this
investigation provide support for a number of concepts developed by prior authors.

When comparing the results of this investigation with the views of the
nature of engineering presented in the NGSS Framework for K-12 Science Education
(NRC, 2009) two concepts are missing. First, the theme Collaborative is not
emphasized in the Framework. One of the participants of this investigation noted
repeatedly that although collaboration was important to engineering, it was not unique
to engineering. Despite not be unique to engineering (like the theme Creative and
Requires Communication), the participants rated these concepts as being important to
K-12 engineering. Many viewed collaboration as being critical to engineering problem solving. Some participants made the case that engineering provided one of the best places to teach students how to solve problems in a group. Without collaboration, this type of group problem solving would not be successful. This is an area that could be emphasized in future K-12 engineering standards. The final area not addressed in the NGSS Framework is the uniqueness of engineering as a way of knowing. When reading both the NGSS framework and the standards themselves, engineering is presented as being similar to science. While the Framework points out that the goal of engineering (to solve technical problems) is different than science (to answer questions about the natural world), it also presents a list of eight practices that mostly shared by engineering and science. Students viewing this list of practices could conclude that science and engineering are largely the same endeavor. Cunningham and Carlsen (2014) have argued that the simplified NGSS presentation of engineering may actually misrepresent the practices of engineering and confuse students. In contrast, a majority of participants in this investigation made it clear that they saw engineering as unique and different than science in many ways. Rather than engineering being only an application of science, many participants described engineering as generating its own knowledge. Some participants described engineering as using the tools of other fields (such as science and mathematics). They described science and engineering being linked because engineering develops new technologies that then can be used to conduct better science. This view of the
uniqueness of engineering is not emphasized in the Framework and is also not included in the K-12 engineering teacher standards (ASEE, 2014a) or in Karatas (2009) list of tenets of the nature of engineering. It is recommended that this view of engineering be expanded in future K-12 engineering standards so that student understand that engineering is not simply a part of doing science.

This investigation takes an empirical look at aspects of the nature of engineering that are important for K-12 engineering education. With the inclusion of engineering in the NGSS, a much greater number of students have the potential to learn about engineering in their K-12 education than ever before. With this greater visibility comes the potential for diluting the meaning of engineering so much that students graduate from high school with an incomplete view of the nature of engineering. As the field of K-12 engineering expands, it is important to build it on a solid foundation. This investigation attempts to begin the work of building an empirical foundation for the nature of engineering that will help students gain a more complete view of the field of engineering. Because K-12 engineering curriculum is early in its development, it is hoped that the nature of engineering be included as a foundational understanding throughout all grades and curriculum. Future research needs to validate and expand the concepts developed in this investigation so that a strong empirical basis can be made for important aspects of the nature of engineering.

This work is important because prior studies have not developed a consensus on the nature of engineering for K-12 education. It is hoped that this consensus view will...
support future research and curriculum development. If students have the opportunity to understand the nature of engineering in their K-12 education, it is hoped that they will be literate in engineering and perhaps choose to pursue engineering as a career.
Literature Cited


Hadjigeorgiou (Eds.), Proceedings of the ESERA 2013 Conference: Science Education Research For Evidence-based Teaching and Coherence in Learning (pp. 131–142). Nicosia, Cyprus.


perspectives. Proceedings of the Frontiers In Education Conference (pp. 11–16). Milwaukee, WI. doi:10.1109/FIE.2007.4417827


Nvivo qualitative data analysis software (Version 11) [Computer Software], 2015. Victoria, Australia: QSR International Pty Ltd.


