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Title: Aspects of the Nature of Engineering for K-12 Science Education: A Delphi Study

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Recent state and national standards have increased the interest in engineering at the K-12 level. Science standards, in particular, have begun to make the case for including engineering throughout the K-12 scope of study. Despite the increased attention to engineering, the characteristics and uniqueness of the field of engineering are not clearly defined. Current policies and curriculum often present engineering in a narrow way – primarily as design. The goal of this dissertation is to elucidate aspects of the nature of engineering that are appropriate to teach at the K-12 level.

A panel of experts in K-12 engineering education was convened to participate in a classic, three-round Delphi study. A total of 610 participants (science teachers, engineering teachers, science education faculty, and engineering education faculty) responded to notices posted on national educational association email lists. From the qualified respondents, a subset of 25 participants from each group were chosen randomly (for a total of 100) to participate in the survey. Of the 65 panel members

that completed Round 1 of the survey, 60 also completed Round 3 for a retention rate of 92%.

The panel of experts identified eight aspects of the nature of engineering they believed were important to K-12 education. These aspects were proposed by participants in Round 1 in response to an open-ended question and refined through Rounds 2 and 3 using a Likert-type scale of importance. Participants identified the following aspects as important: *Divergent, Creative, Iterative, Model-driven, Communicative, Constrained by Criteria, Collaborative, and A Unique Way of Knowing*. In addition, participants who completed all three rounds of the Delphi process were asked to provide a succinct definition of the nature of engineering. After qualitative coding, the nature of engineering was identified as "An iterative process that uses mathematics, science, criteria, and constraints to design solutions to human needs or wants." The present investigation provides an empirical basis for target concepts of the nature of engineering at the K-12 level. This work is important to support development of policy, curriculum, instruction, and to provide a foundation for improved science education.

Aspects of the Nature of Engineering for K-12 Science Education:
A Delphi Study

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Brian D. Hartman, Author

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CHAPTER 1 -- INTRODUCTION

The Problem

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, increasing 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) and the National Academy of Engineering (NAE) 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 is not yet clear which engineering "core ideas" will best leverage student knowledge of STEM (science, technology, engineering, and mathematics) disciplines (Moore et al., 2015). K-12 engineering, like science, can be seen a containing three domains: A body of knowledge, a set of practices or methods, and a way of knowing or the nature of engineering (Pleasants, Spinler, & Olson, 2016; American Society for Engineering Education, 2014a; 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 engineers arrive at knowledge, the history of the field, and social practices of engineering) 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.

The engineering field has not always been seen as important to K-12 education. Starting with the Greek philosophers of 500 BC, the “practical arts” were considered less important than the intellectual arts. Students in classical schools began their educational career learning the trivium which consisted of grammar, logic, and rhetoric. After mastering this material, the student moved on to the quadrivium, a program of study consisting of arithmetic, geometry, music, and astronomy (Vos, 2003). These subjects covered the breadth of “high minded” subjects considered to be worthy of study. A prioritization of subjects in the academic arena has remained to modern times (Robinson, 2011). As education reformers have pointed out over the years, one problem with an overemphasis on the “intellectual curriculum” can lead to is students graduating from college without the ability to apply basic science concepts such as describing moon phases or wiring a simple bulb to a battery (Lopez & Schultz, 2001; Schneps, 1998). The “practical arts” offered as part of the U. S. high school curriculum have been concentrated in career and technical education tracks which are taken by a small percentage of students (US Department of Education, 2013). This means for most students, engineering, with its emphasis on practical realities, is typically relegated to post-secondary education where a small percentage of students are exposed to its concepts.

This restricted view of engineering has started to change. Society has come to recognize that engineers have been responsible for improving the lives of the average person. Despite the negative image of practical engineering retained from the ancient philosophers, engineers have been raised to icons in popular culture. Steve Jobs, a technical designer, was brilliant at attracting exceptional engineers who had ability to translate his designs into electronic devices that met people's needs (Belk & Tumbat, 2005). The ubiquity of these electronic devices and the increasing role of the Internet in daily life have placed engineers increasingly at the center of innovation, prosperity, and national pride. Looking to the future, many of the challenges humanity faces such as meeting growing energy demand, solving water shortages, and improving urban life, all require engineering knowledge and skills to solve. In fact, parents now rate engineering as the top profession they would recommend for their children (The Harris Poll, 2014). The upgraded status of engineers, along with a national need for more engineers, has brought the field onto the center stage in education.

In 2013, the Next Generation Science Standards reflected the growing interest in K-12 engineering by integrating it within 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 understanding of the field of engineering if they are to make these significant changes to their teaching practice.

Current efforts to teach engineering in K-12 education often focus on engineering design instead of addressing the larger picture of the nature of engineering. Of the 41 US states that include some form of engineering in their educational standards, 73% present engineering only as technological design or primarily as a component of technology (Carr, Bennett, & Strobel, 2012). Moore et al. (2015) have developed a set of 12 criteria that can be used to evaluate state engineering standards to determine their completeness. These criteria are based on outcomes developed for graduating college students by the Accreditation Board of Engineering and Technology (ABET) and modified for K-12 use. The criteria include concepts such as the process of design as well as more philosophical ideas such as conceptions of engineering and the interdisciplinary characteristics of engineering (that would include the nature of engineering). Comparisons of the Moore et al. engineering framework against state engineering standards shows that most states have relatively incomplete standards. Only three states (6%) include all 12 criteria of the Quality Framework (Moore et al., 2014). Most of the other states (66%) implemented less than 80% of the criteria. This result points to a limited view of engineering in state-level standards. This means that students may be learning a narrow view of engineering in schools that implement the standards.

While the NGSS emphasize design as the primary activity of engineering (NGSS Lead States, 2013) it also makes it clear that engineering is broader than this single concept. 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 (Carr et al., 2012; Moore et al., 2015). 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.

Definitions

Approximate truth

The term ‘approximate truth’ is used in two ways in this work. First, the goal of the Delphi process is to develop approximate truth through the consensus of experts regarding a new field. Even in established fields, it is difficult know anything with certainty. This is especially true in rapidly developing fields that are not fully defined. The fields of both engineering education and philosophy are relatively new. Although some work has been done in recent years, these fields do not yet have a large body of study to draw from. Engineering has been brought into the K-12 classroom through recent state and national efforts. Despite the lack of consensus among educators and philosophers on the nature of engineering, appropriate K-12 learning goals need to be developed. The value of a Delphi study in these situations is to develop a framework based on an approximation of truth in a way that can be justified in a rational way (Linstone & Turoff, 2002). In this manner, concepts useable for K-12 education can be developed and made available for teachers and researchers to employ.

The second use of the term ‘approximate truth’ concerns the nature of engineering itself. Engineering knowledge is different than the knowledge of science (Bucciarelli, 2003). In science, the goal is to develop investigations that will point to universal principles of the underlying structure of the universe. Science attempts to develop universal truths that will be applicable in all situations, even though it is understood that such generalizations can never be true in the absolute sense. By contrast, the goal in engineering is to develop local knowledge that will allow the solution to meet the requirements of that specific situation. There is no 'best' design for a particular problem. Instead, the engineer develops 'approximate truth' that optimizes the design for the scenario in which he or she is working. Other engineers may solve the problem in another way. The fact that engineers often value the creation of useable knowledge over universal principles is one of its distinguishing characteristics (Goldman, 1990).

Engineering

Engineering is an activity that attempts to solve technical problems for clients. The ultimate goal of engineering is to meet the perceived needs of its customers and stakeholders. Engineering focuses its efforts on designing artifacts and developing manufacturing systems (Vincenti, 1990). While the historical meaning of the term *engineering* has meant developing or devising the meaning of technology is not as clear-cut ("Engineering", 2016). The root word *techne* originally meant the skill to produce something. This word would have been used to describe the skill of building a boat or writing a poem. Today, however, craft refers to skills necessary to build a physical object. *Technology* is now seen as the products that meet human needs. The output of engineering activity is thus technology. Engineering, therefore, has a close relationship to technology. Technology is the tool that engineers create that meets the needs of customers or stakeholders. In common current usage, the distinction between engineering and technology is that engineering is the process that develops the solution, whereas technology is the solution itself.

Engineering Design

Engineering design can be defined as the process of developing unique products by balancing constraints and applying knowledge of the built world (Cross, 2011). This process develops a solution that meets the needs of a specific user or set of users. Engineering design is the main activity of engineering just as inquiry is the main activity of science. In both cases, these core activities bring together and employ bodies of knowledge and professional practice.

Nature of Engineering

The nature of engineering can be defined as aspects of engineering knowledge understood from philosophical, historical, and sociological perspectives (Lederman, 2006). From a philosophical perspective, engineering epistemology represents a distinct way of knowing compared to other disciplines, such as mathematics or science (Goldman, 1990). Despite (or perhaps because) of its uniqueness, a consensus on the epistemology of engineering has not been developed (Bucciarelli, 2003; Frezza & Nordquest, 2015). Two major approaches to epistemology have been proposed. First, that engineering has an integrated epistemology that merges the epistemologies of business, science, design, and practical realization (Figueiredo, 2008). This approach is unsatisfying because it implies that engineering does not have a unique perspective on knowledge. The second approach to engineering epistemology is based on

American Pragmatism (Goldman, 2004). Engineering knowledge, seen through the lens of this philosophy, is developed using social values and concrete action. The knowledge that is most valued by an engineer helps him or her solve a problem (action) that meets the needs of stakeholders (social values). While the epistemology does not yet have widespread support in engineering philosophy, it has the potential of providing one possible unified epistemology of engineering.

Problem Statement

The next steps in expanding the K-12 understanding of engineering are to develop a nature of engineering framework that will assist policy makers, researchers, teachers, and students in understanding the nature of engineering. Engineering has not yet developed a consensus regarding the nature of the field (Karatas, 2009). An age-appropriate understanding of the nature of engineering will support K-12 teachers in helping students to internalize engineering and understanding how it is different than science. State engineering standards need to be re-evaluated to include a broad view of engineering (Moore et al., 2015). By improving our understanding of the nature of engineering, educators will better understand how, where, and why engineering fits into the STEM curriculum. The purpose of this investigation is to develop a consensus framework for the nature of engineering for K-12 education using the Delphi methodology.

The primary research question for this work is therefore, “What aspects of the nature of engineering should K-12 science students learn?” Subsidiary research questions include:

1. How do experts describe aspects of the nature of engineering they view as valuable in K-12 education?

2. Which aspects of the nature of engineering do engineering experts believe are important for K-12 education?

3. What priority do engineering experts give important characteristics of the nature of engineering for K-12 education?

4. How to experts succinctly define the nature of engineering?

Significance of Investigation

Engineering is now part of the K-12 curriculum standards nationally and in many states. Efforts are already underway to develop curricula that meet the new standards, but the role of engineering in STEM subjects is still developing (Barber, Fernandez, Roseman, & Stark, 2015). This investigation will inform engineering curriculum development for the K-12 classroom by developing an understanding of the nature of the field. If engineering is presented only as design, students will see only one aspect of the field. If a more complete view of the nature of engineering is presented including content, practices, and epistemology, then students will have the opportunity to understand the field of engineering from a deeper perspective. A better understanding of engineering by students has the potential for improving engineering literacy and inspiring a broad range of students to explore the field for future careers.

The goal of this investigation is to develop a framework for the nature of engineering that is appropriate for K-12 STEM education. The results of this investigation will inform research, policy, and curriculum development for the K-12

STEM disciplines. Curriculum developed with a rigorous, research-based view of the nature of engineering will encourage a much deeper understanding of the field in K-12 education. Having an understanding of the features of the nature of engineering will support the development of assessment techniques to better understand student and teacher views on the subject. These efforts will help outline more informed ways to teach engineering in the K-12 STEM curriculum and will better prepare students for decision-making in a technological world.

CHAPTER 2 -- LITERATURE REVIEW

Introduction

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 the value of this line of research to the science education community.

The nature of science was identified as an important concept for scientific literacy by the 1960s. Pella, O’Hearn, and Gale (1966) completed an exhaustive review of the literature and identified the nature of science to be the third-most referenced concept. Early K-12 research on the nature of science focused on student and teacher conceptions (Lederman, 1992). Researchers found that both teachers and students had view of the nature of science that were not in line with national organizations such as the NSTA (National Science Teachers’ Association) and the AAAS (American Association for the Advancement of Science). Much of this research on the nature of science was completed using convergent, quantitative techniques that did not uncover the breadth of thinking about the topic. Researchers (Aikenhead, 1988; Lederman, Wade, & Bell, 1998) argued for the use of quantitative approaches so that student and teacher understandings could be better understood. They point out that students responding to nature of science quantitative questionnaires might have understood the questions differently than the researchers. They argued this issue could be resolved by using qualitative methods (open-ended questions and interviews) to understand what the students actually understood about the nature of science. The following review of literature related to K-12 conceptions of the nature of science focuses on the development of the tenets of the nature of engineering and does not emphasize the development of the Views of the Nature of Science Instrument. The development of the key aspects of the nature of science is valuable to the development of aspects of the nature of engineering for K-12 use.

Citing a poor understanding of actual student beliefs about the nature of science, Lederman and O'Malley (1990) developed an open-ended survey for use with K-12 students. Rather than focus on a multitude of beliefs about science, the survey and follow-up interviews examined student views about the tentative nature of science. The authors chose this aspect of the nature of science because they believed tentativeness is a U aspect of the nature of engineering and K-12 students of all ages are able to understand this concept. The nature of science concept investigated in this investigation (Lederman et al., 1990) and the qualitative approach to understanding student views became the foundation for future research into the nature of engineering.

Additional tenets of the nature of science were added to assessments late in the 1990s. Abd-el-Khalick, Bell, and Lederman (1998) investigated the nature of science conceptions held by pre-service teachers. They examined student understandings before and after participation in a year-long teacher preparation program that emphasized the nature of science. The program used a series of 15 activities that each highlighted an aspect of the nature of science. The concepts emphasized in the program were, "…Tentativeness in science, the theory-laden nature of scientific observations and inferences, the use of creativity in the development of scientific knowledge, and the necessity of empirical evidence" Abd-el-Khalick et al. (1998). Two additional items were added to the list (for a total of seven) in subsequent research by Abd-el-Khalick (1998b) in his unpublished dissertation. The two additional items emphasized the social and cultural embeddedness of science as well as the difference between theories and laws. Abd-el-Khalick (1998b) developed a set of open-ended questions using these nine tenets of the nature of science. He used these questions to assess university student understanding of the nature of science. The list of tenets of the nature of science developed by Abd-el-Khalick (1998b) developed was the basis for developing the Views of the Nature of Science questionnaire in the 2000s.

Lederman, Abd-El-Khalick, Bell, and Schwartz, (2002) developed an open-ended instrument that used qualitative analysis to gain an understanding of conceptions of the nature of science. The authors recognized that was disagreement among scientists, historians and philosophers regarding the important concepts of the nature of science as noted by Smith, Lederman, Bell, Mccomas, and Clough (1997). Lederman et al., (2002) argue that the disagreements that do exist are largely irrelevant to K-12 education. Notwithstanding this lack of consensus, Lederman et al. (2002), makes the case that at a high level of generalization, sufficient agreement exists to develop a set of understandings about the nature of science. The instrument they developed is organized around a set of seven tenets of the nature of engineering they feel are general enough to be universally applied. Each tenet was chosen based on two factors: Whether a concept had broad agreement among philosophers, historians, and sociologists of science and whether the concept was accessible or relevant to K-12 students. Table 1 outlines each tenet and a brief description of each concept. The authors acknowledged that they are presenting *a* view of the nature of science rather than the *one and only* view of the nature of science. This perspective was an extension of prior work done on the nature of science (Abd-el-Khalick et al., 1998a; Abd-el-Khalick 1998b; Lederman et al., 1990) and a description of the various version of the assessment. The authors describe the method used to develop the list of tenets as being developed organically from the literature as the assessment techniques matured (see Table 2 for a developmental view of the development history). The seven tenets proposed in this paper are still in use today as evidenced by the fact that Lederman et al. (2002) was referenced in peer reviewed publications 128 times in 2015 alone, almost a decade and a half past its publication (Google Scholar, 2016). This paper (Lederman et al., 2002) became the reference for a large body of work on K-12 nature of science research.

The approach taken by Lederman et al. (2002) in the development of aspects of the nature of science is not without issues. Rather than develop the list of tenets through empirical means, the authors based the list on concepts they identified as having some level of general acceptance and being accessible to K-12 students. While this list may have been useful in moving the field forward, there is no evidence that it had support among science teachers and science education researchers. Without the link to empirical evidence, the potential for researcher bias is increased. Confirmatory research that utilized feedback from an adequate number of participants would strengthen the choice of tenets to emphasize in nature of science research.

Osborne, Collins, Ratcliffe, Miller, and Duschl (2003) completed an investigation to develop a list of nature of science concepts that minimized researcher bias. While acknowledging disagreements existed in the nature of science field (Smith et al., 1997), the authors took the approach that it was possible to develop a consensus on the topic. They sought to determine empirically "…Whether there was a measure of consensual agreement within the expert community for an account of the nature of science, albeit reduced, contestable, and simplified, that might be offered to school students" (Osborne et al., 2003, p. 697). The project used the Delphi methodology to encourage controlled debate and feedback among a diverse group of experts in the field of the nature of science. In contrast to the widely debated Alters (1997) investigation that surveyed philosophers of science, Osborne et al. (2003) wanted to develop a consensus from a broad group of scholars. For the investigation, they recruited 23 participants from scientists, science education researchers, K-12 science teachers, science communicators, historians of science, philosophers, and sociologists of science. Rather than use a set of questions designed to elicit responses on pre-determined aspects of the nature of science, Osborne et al., (2003) developed a small number of open-ended questions that would allow respondents to describe their varied views of the field of science. The goal was to determine what students in K-12 education should be taught about the nature of science. Given the diverse set of participants and the open-endedness of the prompt, the researchers were setting the stage to develop a set of conceptions about the nature of science with minimal a priori structure.

The Delphi methodology used by Osborne et al. (2003) utilized three rounds to improve the development of consensus without face-to-face interaction. The first round, qualitative in nature, asked the participants to respond to three questions designed to elicit responses on three aspects of science. The questions asked were,

1. “What, if anything, do you think should be taught about the methods of science?

2. What, if anything, do you think should be taught about the nature of scientific knowledge?

3. What, if anything, do you think should be taught about the institutions and social practices of science? (Osborne et al., 2003, p. 669)

Note that only one question pertained directly to the nature of science while the other questions were related to tangential concepts. The responses from Round 1 were similar to a brainstorming session where many ideas are presented without limiting criteria. Responses were qualitatively coded to identify thirty themes related to the initial three questions. These aspects were developed into a survey that allowed participants to rate each theme on a Likert-type scale between 1, non-essential, to 5, being essential. After rating the themes in Round 2 participants were sent a final survey that contained the themes from Round 2, their mean and standard deviation and a summary of comments made by other participants. The final results provided a list of themes that were ranked as well as focused on the most important items. Although the researchers reported items by questions in Round 2, they collapsed all the themes into one table into Round 3. Therefore, it was necessary to make assumptions about which items were related to the nature of science in Round 3 based on the results from Round 2. In the final list of items that showed consensus as well as stability of rating between rounds, nine items related to the nature of science remained. These items are listed in Table 3 in comparison between the seven tenets of the nature of science developed by Lederman et al. (2002). It can be seen that most of the Lederman et al. (2002) concepts were also identified by Osborne et al. (2003). Although the wording of each concept is different, commonalities appear. Only one item, distinctions between theories and laws, does not appear to be present in the Osborne et al. (2003) list. This investigation served to validate the Lederman et al. (2002) concepts developed for the nature of science by empirically finding similar themes. The Osborne et al. (2003) paper is the second-most cited paper that references Lederman et al, (2002), with 704 citations (Google Scholar, 2016). The two papers support the field by providing two similar views of the nature of science.

A few criticisms may be raised regarding the Osborne et al. (2003) methodology. First, it is not clear why they chose three questions to initiate Round 1. They made the case that the investigation would stimulate open-ended thinking about the nature of science. However, creating a tripartite division in Round 1 artificially constrains the brainstorming on three separate topics; methods of science, nature of scientific knowledge, and social practices of science. This approach starts the conversation off with *a priori* views of what constitutes the nature of science. Second, the panelists chosen do not all appear to have knowledge of K-12 education. Because the investigation intended to determine what ideas were appropriate for K-12 education, it is imperative that all panel members have an expert knowledge and/or experience of this level of education. Of the five groups of participants (scientists, historians, philosophers, and sociologists of science, science communicators, science teachers) only the science teachers are certain to have expert-level knowledge of K-12 students' needs. Although science educators and other groups may have K-12 experience, this criterion does not appear to have been used in the selection of panels. Finally, Osborne et al. (2003) performed inferential statistical analysis on the results of the investigation to determine whether individual groups had statistically different responses to individual items. Given the purposive selection methodology for participants, this approach does not meet a key assumption for the use of the ANOVA method (Hahs-Vaughn & Lomax, 2012). The foundation of inferential statistics relies on the random selection of a sample of a population that would have a normal distribution. Osborne et al. (2003) compares five groups using ANOVA, even though he purposely selected each member of the panel. He reports that there was no significant difference between the groups studied. The group members were not selected at random from a larger population, so the results he reports do not flow from the methods he used. Using inferential statistical analysis on non-probabilistic samples confuses the research methodology and researchers should not make claims about populations (Argyrous, 2011). This has the potential to lead the authors to make unsubstantiated claims about groups in the population.

Two complementary approaches have been used in the development of the nature of science tenets for K-12 education. The first approach used by Lederman et al. (2002) synthesized the literature on the topic and developed set of tenets appropriate for K-12 students. This group developed the list of tenets in conjunction with the development of the Views of the Nature of Science Questionnaire. After each version of the questionnaire was developed, it was piloted with students and the tenets revised if necessary. Throughout this iterative process, the full list of seven tenets was developed. The Osborne et al. (2003) group approached the development of nature of science concepts using empirical methods. They used the well-established Delphi to develop a consensus among experts in the field. After multiple rounds of this process, the list they published has many similarities to the list of seven tenets developed by Lederman et al. (2002). The overlap between the results of these two approaches points to some level of agreement in the field of K-12 nature of science research.

Greek Foundations of Engineering Epistemology

Philosophy seeks to understand sources of human knowledge since the early Greek philosophers. Beginning with pre-Socratic thinkers such as Pythagoras and Anaxagoras, the Greek culture encouraged the development of thinking deeply about the universe and knowledge itself. Xenophanes, a philosopher who lived roughly 2500 years ago, was one of the first to ask questions about how knowledge is obtained (Kattel, 1997). One hundred years later, Plato examined issues of human knowledge in his work the Theaetetus, but did not differentiate epistemology as a separate field of investigation (Laidlaw-Johnson, 1997). Later philosophers did divide the field of philosophy into separate branches. For example, the Stoics (circa 200 BC) partitioned philosophy into the investigation of metaphysics, ethics, and logic (Masih, 2013). Despite having a long history of inquiry through the Renaissance era, the word epistemology was not introduced into English as a branch of philosophy until James Frederick Ferrier coined the term in the 1800s (1856). The investigation of the theory of knowledge (epistemology) has become one of the major divisions of philosophy in modern times. As used today, epistemology is defined as "The investigation of the nature, origin, and limits of human knowledge" ("Epistemology", 2016). Of these three sub-divisions of epistemology, the nature of knowledge is the focus of this paper, especially as it relates to K-12 science and engineering education.

The sciences have been at the forefront of philosophical discussions of the nature of knowledge, perhaps because of the often-stated goals to understand the world in an objective way. Aristotle described science knowledge as universal claims that are the results of the process of reasoning from cause to effect in a way that eliminates personal bias (May, 2011). In the thousands of intervening years, many proposals have been made about the nature of scientific knowledge. Despite competing ideas on this topic, the nature of scientific knowledge can be described in terms many will agree on. Nature of science concepts of value to primary and secondary education are often topics that have some level of consensus among the philosophy of science community (Smith et al., 1997). Areas of disagreement are often in the more nuanced views of science and philosophy. As discussed above, Lederman et al. (2002) identified consensus concepts appropriate for K-12. This viewpoint provides nature of science concepts that can be useful for K-12 educators and researchers.

Engineering vs. Science

Recent interest in engineering education has sparked a debate on whether the nature of engineering knowledge is the same as this consensus view of the nature of science. In other words, is engineering distinct enough from science that a separate theory of knowledge exists? This issue has become more important since the Next Generation Science Standards (NGSS) identified engineering and science practices as being equally important to K-12 science education (NRC, 2011). Although it appears that a majority of the philosophical work on the nature of engineering has been performed at the professional or university level, an evolving body of work serves to inform K-12 education. It is important to understand whether engineering epistemologies are different from science epistemology so that students can come to understand engineering as a unique way of knowing.

In an attempt to answer the question of whether engineering has a unique way of knowing, recent philosophers have explored the field of engineering and proposed that a difference exists. Walter Vincenti (1990, pp. 200-240) set the stage for this discussion by arguing that science and engineering represent two different types of knowledge. Scientific knowledge usually means the work output of a scientific investigation -- knowledge generated but often not used. By contrast, engineering knowledge typically refers to information used by engineers in their practice. For the engineer, being able to successfully and practically use knowledge is part of what determines the veracity of the knowledge. This perspective means that engineers are less interested in developing an overall model of a phenomenon that will make sense of all the observations. Instead they are more likely to use larger theories to predict how alternate designs will operate (Bucciarelli, 2003). This process of reasoning from general to specific is one area that sets engineering apart from the enterprise of science. It is the very specificity of knowledge that allows an engineer to achieve practical results. The goal of a typical engineer is to create an artifact that accomplishes certain functions using physical materials. Engineering knowledge gained in this way becomes a collection of solutions to problems that the field has encountered. By contrast, the ‘epistemic destiny’ (Muller, 2009, p. 210) of knowledge developed in science is to become more abstract and general. This scientific knowledge is often pursued with the primary purpose to understand and disseminate the workings of the natural world.

The contrast between the goals of engineering and science helps to explain why engineering is not simply applied science. While engineers do use scientific knowledge in the course of their work, they also generate their own knowledge about the world. As an example, much of the engineering knowledge developed about bridge materials (such as steel and concrete) was developed by engineers to understand how these materials withstand the forces of tension and compression. This type of knowledge is pursued not to develop a theory of molecular bonding in concrete and steel, but to understand how it behaves in specific conditions. This knowledge is used as a tool to accomplish the unique goals of engineering, which are to solve a practical problem using technology. Therefore, engineering is as much applied science as physics is applied mathematics (Goldman, 2004). The tools used in an activity do not define the activity itself. Instead, the purpose of engineering defines the knowledge it generates.

The unique goal of engineering defines methods that are also distinct from science. One methodology used in science involves developing a hypothesis and testing it. This process often involves starting from a theory or an understanding of the phenomena and developing a deductive proposition. If the hypothesis is correct, then a predicted result must be seen in the experiment. If the correct result is seen in the experiment, then the hypothesis must be true. By reasoning from the top down, the scientist is able to generate general theories of how the world operates. By contrast, engineers often employ inductive reasoning in the pursuit of their understanding of practical phenomena (Bianchi, 2010). By this logic (also called abductive reasoning) the engineer will seek causes for the results of an experiment. After examining the potential causes of a particular result, she will infer the most probable cause based on the best explanation. While this type of reasoning is used in some areas of science (Darwin developed his theory of evolution using this method) it is widely used in engineering (Bianchi, 2010). It is common to have a single case, such as a bridge collapse, with multiple competing causes. The job of an engineer in these situations is to determine which explanation makes the most sense given the information. By the logic tools most commonly employed, engineering and science operate differently. As discussed earlier, science and engineering approach knowledge in very distinct ways: Abstract vs. practical, development of unique knowledge, and specific vs. general. These differences make the case that engineering epistemology represents a unique and distinct approach from the epistemology of scientific knowledge.

Mixed Epistemologies

If indeed engineering epistemology is distinct from science as has been argued what are the characteristics of this view? In other words, how do engineers judge whether their perspective is a 'justified true belief' or simply opinion or illusion (Plato, 369 BC / 1921). This question has been answered from a number of perspectives in this nascent field of engineering philosophy. One perspective proposed by Figueiredo (2008) has been to identify the various roles of engineering in society and then determine the philosophical perspective that is used to verify knowledge in that realm. This view identifies engineering as a transdisciplinary

(Gibbons et al, 1994) profession, which includes components of multiple disciplines. Figueiredo (2008) categorizes engineering into the following four dimensions: Basic science, social/business, design, and doing (practical realization). The engineer would therefore consist of a combination of these qualities. In their basic science role, engineers apply science and perform experiments to validate hypotheses. This role inherits a strong positivist philosophical history from the natural sciences (Figueiredo, 2008). In the social/business role, the engineer must understand the needs of the customer, the user, and society at large. Engineering products are not successful if they do not meet the economic realities of the group that commissioned it. This role brings a historically positivist perspective, but increasingly is including constructivist viewpoints (Figueiredo, 2008). In the designer role, the engineer must navigate competing requirements and constraints in order to develop a product that satisfies the multiple stakeholders of the project. This role brings the engineer into a world that is quite different than science. They must use systems thinking rather than analytical thinking. The engineer must seek compromises, re-negotiation, and look for alternative solutions while making decisions based on incomplete knowledge and intuition. This role necessitates an epistemology that emphasizes constructivist and interpretivist perspectives (Figueiredo, 2008). Finally, the engineer is a doer and a master at getting things done. In this role, he or she must identify barriers to be overcome and exhibit flexible perseverance. This role emphasizes constructivist and interpretivist views of knowledge due to the rapidly changing landscape of a product under design (Figueiredo, 2008). With these four perspectives in hand, Figueiredo

(2008) proceeds to describe engineering epistemology as the amalgamation of the philosophical perspectives that each of the four roles present. It is difficult to map such an epistemology without resorting to what Levi-Strauss (1966, p. 22) calls ‘bricolage’ in some manner. As a type of handcrafter, the engineer uses the odds and ends philosophical tools at hand to rough out the solution they need regardless of the approach. While Figueiredo’s (2008) approach does provide an explanation for the many philosophical viewpoints engineers must take in their work, it does not provide a holistic epistemology of engineering.

Pragmatism

Although a comprehensive epistemology of engineering has not yet been fully developed, I argue that pragmatism can provide a holistic epistemology to guide engineering education. The following is an outline of the history of pragmatism as presented by Goldman (2004) and the potential for this line of thinking to support an integrated engineering epistemology. If this view were developed more fully, it is possible that engineering would have a coherent epistemological stance. Engineering has been undervalued in philosophy and academia in general since the Greek era. Plato and Aristotle argued for a philosophy that developed unchanging and eternal principles that could be applied universally. In fact, Aristotle (350 BC / 1964, 1357a) argued action (practical fields) could not be investigated by science because it did not meet these criteria. Mathematics embodies the epitome of high philosophical thinking and consequently is given the highest value in the western philosophical tradition. Mathematics, as Goldman (2004) notes, is universal, not subject to value judgments, and its answers are timeless. In contrast, engineering is driven by a need to create in the real world, which may not involve the pure deductive reasoning so prized by the Western mindset. Engineering is filled with value judgments, is very specific to a given context, and subject to great uncertainty. Consequently, it has long been assumed to be far beneath the purview of classical philosophy Goldman (2004). Science has inherited the mantle of philosophical respectability by adopting mathematical, deductive reasoning as it primary logic. With its emphasis on investigating an “objective reality”, it has placed itself in a position to garner attention as an object of philosophical analysis. Thus, engineering and science ended up on opposite sides of a philosophical divide. Until recently, engineering has been subordinate to the philosophical analyses of science and its cousins.

In the Renaissance, as Goldman (2004) describes it, a new breed of philosophy began to take hold. The Humanists started to value the more practical aspects of knowledge and revived a number of classical engineering texts. This effort seeded a technical resurgence that eventually expanded into the Industrial Revolution. Starting in the 1870s, American Pragmatism provided an action-oriented balancing effect to the rationality of the Western philosophical tradition. Dewey himself not only saw engineering as important, but he also viewed science as a type of engineering (Dewey, 1960, p. 84). In his view, the action embedded in engineering and technology provided a foundation from which scientific research could grow. Dewey (1960) argued that “Knowing is itself a mode of practical action and is the way of interaction by which other natural interactions become subject to direction” (p. 107). This elevated the perspective of engineering and other practical arts to a preeminent position in his pragmatic philosophy and paved the way for the current renewal of philosophical interest in engineering philosophy.

Using pragmatic thinking as a lens, the nature and practice of engineering comes into focus as a unique way of knowing. Rather than emphasizing the logical 'science' of engineering, this viewpoint (as described by Goldman, 2004) explores how engineering negotiates the interconnected, value-laden world of technology. In recent years, even the basic sciences have come to see a networked view of reality where sub-atomic particles are influenced by human observation and where biological molecules (of proteins and DNA) are intimately linked via myriad feedback systems. A theory of pragmatic engineering knowledge based on this philosophy is constructed using social values and action to build a reality that resolves societal issues. An engineering practice built on these principles emphasizes the social role of the engineer and engineer as social scientist, designer, and practical realizer (Figueiredo, 2008). While the view of the engineer as a scientist has brought with it the prestige of the philosophy of science, a renewed focus on practical aspects of engineering could provide an opportunity for fruitful research in the future. By default, this view reduces the emphasis on the traditionally positivist methods of engineering research and encourages a more interpretivist approach to understand social networks and the practices of product realization.

<u>Nature of Engineering -- Standards</u>

It is clear from a review of literature that the philosophy of engineering is early in its development and a consensus on the epistemology of engineering has not yet emerged. This lack of philosophical consensus does not indicate effort into developing a K-12 approach to the nature of engineering would be futile. The field of science had a similar problem in the early 1950s when initial nature of science work was started. Lederman et al. (2002) made the case that despite the lack of agreement among philosophers, a consensus could be reached on points appropriate for K-12 students. This point was borne out by Osborne et al. (2003) in his Delphi consensus investigation on the nature of science that showed there were many tenets that experts agreed upon. Despite the lack of agreement among philosophers on the nature of engineering, various non-empirical efforts have been made to clarify the features of the nature of engineering.

National (United States) science standards have been a driving force in the inclusion of engineering in science content. In 1989, the Association of Americans for the Advancement of Science (AAAS) published a document called *Science for all Americans*. In this unique perspective, technology and engineering were given a prominent place in the quest to define what students should learn about science. In a chapter devoted to the nature of technology, AAAS (1989) defines engineering using the following characteristics: “Uses knowledge of science and technology, solves practical problems, and designs solutions.” The report goes on to compare the nature of engineering with the nature of science stating “Much of what has been said about the nature of science applies to engineering as well, particularly the use of mathematics, the interplay of creativity and logic, the eagerness to be original, the variety of people involved, the professional specialties, public responsibility, and so on" (AAAS, 1989, p. 27). The report goes on to identify working within constraints, tentativeness of designs, cultural context, and the requirement of testing models as being important aspects of engineering. While this report (AAAS, 1989) was not a K-12 educational standards document, it had an influence on the growing standards movement. Future projects would develop specific K-12 standards that included engineering.

At the request of the National Science Teachers Association, the National Research Council began work on the first set of science standards (NRC, 1996). This independent body, funded by both public and private funds, was seen as a way to bring such standards to a national stage. The NRC proceeded with development of science standards by tapping into research expert knowledge and hosting focus groups with teachers. The standards, published in 1996, were the first attempt coordinate science education at a national level in the United States. While these standards did not emphasize engineering, one of the eight standards was titled 'Science and Technology.' Under this heading, the standards called for students to develop experience in technological design, which included problem identification, proposing designs, implementation, evaluate the solution, and communicate results (NRC, 1996, p. 192). Although design was included in the national science standards, engineering was not discussed in the document. In fact, despite being co-sponsored by the National Academies of Engineering, the word engineering only appears two times in the body of the 240-paged document. It would be left to future standards to raise the visibility of engineering in science education.

In 2013, a new set of science standards were released for the United States. These Next Generation Science Standards (NGSS) was developed by a consensus of state-level science policy makers and educators (NGSS Lead States, 2013). The goal of these efforts was to more proactively include state stakeholders and incorporate new research about how students learn science. In contrast to the prior standards, the NGSS explicitly included engineering practices in the standards and engineering concepts are integrated into the requirements for each grade level. In fact, the final NGSS document body included over three hundred references to engineering. Taking advantage of recent research into science learning, the standards also propose a new view of teaching science. Whereas the 1996 approach heavily emphasized content standards, the new standards took a more holistic view of science. Science, under the new perspective, was understood in terms of practices that scientists and engineers enacted in their daily work as well as the knowledge they use. Thus, the NGSS contains three integrated components: Science and engineering practices, disciplinary core content, and integrative links to other disciplines (NRC, 2013). With the inclusion of engineering practices and content on par with those of science, the NGSS made understanding the nature of engineering even more critical.

A perspective on the nature of engineering was proposed as a component of the NGSS project (NRC, 2009). The authors note that natures of engineering and science are similar in some aspects: Require creativity, reasoning from evidence, models, and testing of solutions (NRC, 2009, p. 39). On the other hand, they note that significant differences exist between the two approaches. First, engineering design works under constraints in a different way than science. Engineers must develop solutions that meet stakeholder needs as well as being economically viable and meet all safety requirements, among other constraints. The engineer must trade off various aspects of the design to develop solutions that most closely balance the competing demands. Second, engineers develop solutions to problems, where scientists attempt to explain nature. Scientists develop an explanation of specific detailed phenomena before working up to an explanation of a general rule about nature. In contrast, engineers use general rules about nature to solve a specific detailed problem. Additional characteristics of the nature of engineering listed by the report include: Purposefulness, requirement compliance, systematic, systems thinking, iterative, creative, and allows many solutions. The report (NRC, 2007) paved the way for the NGSS inclusion of engineering as a core concept. However, the nature of engineering is only given a short description and the listed characteristics appear to have been developed by committee rather than through empirical means.

Standards for technology literacy adopted by the International Technology and Engineering Education Association (ITEEA) presented engineering as an important component of K-12 technology education (ITEEA, 2007). In this document, engineers are lumped together with architects, technicians, and computer science professionals. The authors of the report noted that engineering and related disciplines are involved in solving problems. Technological design played an important role in the technology standards. Design, as envisioned by the document (ITEEA, 2007), involves identifying a problem, using creativity to develop potential solutions, working under criteria, iterative testing, and potential solutions. While these aspects of the nature of engineering are not explicitly linked to the nature of engineering, they are certainly related concepts. The technology standards (ITEEA, 2007) represented an important step in bringing engineering into the K-12 curriculum. The concepts the technology standards espouse regarding the nature of engineering, however, also do not appear to have an empirical basis.

In attempt to provide a framework for K-12 engineering teacher preparation, the American Society for Engineering Education (ASEE, 2014a) developed a set of standards that every engineering teacher should know. In 2012, Cheryl Farmer and Louis Nadelson developed a draft set of engineering standards based on their experience in the field and extensive literature review (ASEE, 2014b). They then convened a group of 39 engineering educators to review the draft document and provide input on its development. The final document identified key concepts related to the nature, content, and practices of engineering that engineering teachers should know. They identified engineering as being: Creative, problem solving, collaborative, using engineering design, iterative, design with constraints, a combination of engineering theory and practice, and requiring systems thinking (ASEE, 2014a). This effort has provided a foundation for the development of teacher education programs. While its development included review by a committee of 39 engineering educators, the authors did not report the use of empirical methods to develop the initial concepts.

Empirical work has been completed in the area of engineering content-knowledge important for K-12 to students understand. It is important to recognize that understanding engineering content is different from the nature of engineering. Engineering content is the knowledge and skills that students need to have in order to become an engineer. These skills might include basic computing skills, time-management skills or the ability to understand mechanics (Dearing & Daugherty, 2004). Various efforts have been made to delineate important concepts to teach regarding engineering design (Smith, 2006), outcomes of secondary engineering education (Childress & Rhodes, 2006), core concepts for 6-12 technology education (Childress & Sanders, 2007), and competencies K-12 students should have when starting a university engineering program (Custer, Daugherty, & Mayer, 2010). Custer et al., summarize the results of these empirical studies in their review paper on the subject. While there is bound to be some overlap between engineering content knowledge and nature of engineering (the inclusion of design for example), the goals are different. Learning engineering content is intended to help students develops skills and knowledge they will use in a potential future career as an engineer. Understanding about the nature of engineering will help students understand the field of engineering itself. This type of knowledge has the potential for being much more broadly applicable. Understanding the nature of engineering is important for all students to become technologically literate (ITEEA, 2007). While these efforts serve to provide a framework for developing curriculum for K-12 engineering programs, they do not delineate characteristics of engineering itself.

Although standards efforts such as the NGSS and STL do briefly address the characteristics of engineering in introductory materials, these items are not included in the standards themselves and do not appear to be based on the literature. The nature of engineering is also not addressed by name or emphasized as a topic students should know.

Nature of Engineering -- Research

A limited amount of research has been conducted on the nature of engineering. Some researchers have examined K-12 teachers' views of the nature of engineering in order to understand the perspectives on engineering they bring to their teaching. While these studies do not provide a detailed view of the field of engineering, they provide a perspective into the views of practicing teachers. Cunningham, Lachapelle, & Lindgren-Streicher (2005) asked 106 primarily elementary teachers to complete an instrument called 'What is Engineering' that was developed for elementary students. The instrument provides a series of 16 images for participants to circle if they represent the types of work that engineers do. In addition, participants completed open-ended questions such as "What is engineering?" All the teachers taught science classes between 100 to 200 minutes per week. A majority of the teachers had never used engineering in their classroom (63%) and only 10 percent of the teachers had taught more than 20 engineering lessons the prior year. Over 90% of the teachers were able to correctly identify the type of work engineers do, such as designing things, working as a team, or improving items. When asked what engineers do, 65 percent of the teacher identified engineers as designing new technologies solving problems, developing new ideas, and drafting plans. In addition, 47% of respondents saw engineers using imagination, science, and math on the job. Further, 25% also viewed engineers as solving human problems. Although some teachers had misconceptions (such as believing engineers construct technologies themselves) a majority correctly identified engineers as designers and planners. While this investigation is an improvement on the "Draw an Engineer Test" (Cunningham et al. ,2005) used in the past, it had some issues. First, the authors did not describe how they selected the images used in the instrument. It appears these items were chosen from images drawn in previous "Draw an Engineer Test" studies (Cunningham et al., 2005). Second, the authors did not describe any efforts to establish face validity of the instrument with a panel of experts. This oversight calls into question the results of the investigation and leaves questions unanswered regarding the investigation. Third, the authors (Cunningham et al., 2005) do not describe how the participants were chosen for the investigation. If the participants were not chosen at random from a population, the selection method could skew the results due to the background of the people chosen. Because the investigation was not published in a peer-reviewed journal, it has not undergone a rigorous analysis by researchers. This investigation provides a useful perspective on teacher views of the nature of engineering, but leaves many questions unanswered regarding the test's development.

Lambert et al. (2007) also studied elementary teachers' views of the nature of engineering. The researchers selected teachers who participated in a series of summer academies on P-6 engineering. The goal of the summer academies was to improve teacher understanding of the nature of engineering. Data were gathered over two summer academies, one for local teachers and one that was nationally advertised. Teachers were selected for the professional development based on their teaching philosophy and expressed interest in integrating engineering into the classroom. Teachers were given a pre-test instrument that asked them to answer open-ended questions about what engineering is and what engineers do. Responses were qualitatively coded by multiple researchers to ensure inter-rater reliability. The researchers identified seven categories of responses, three of which were related to the nature of engineering: “Nature of engineering, nature of engineering problems, nature of the solution” (Lambert et al., 2007, pS2B-13). Under these categories, teachers identified the nature of engineering as: Problem based, everywhere, creative, practical, constrained, developed products and systems, and improves products. This list of characteristics of the nature of engineering included similar concepts to the lists in the NGSS and ITEEA standards. The participant group showed a reasonable understanding of the nature of engineering, but individual teachers had a relatively limited view. While most teachers (83%) identified engineers as developing products only a small number (3%) were able to identify engineering as working under constraints. This investigation has some problems that make these results less useful. First, it is difficult to gather an understanding of an individual teacher’s conceptions of engineering with an open-ended question. The problems of this approach can be seen by comparing the pre and post test scores. Despite a two-week intensive workshop, many teachers did not list more concepts in the post test. This highlights the challenge of reciting all possible aspects of an idea in a free-recall situation. Capturing views on concepts as abstract as the nature of engineering may have been better accomplished with an instrument that provides multiple prompts to guide student recall. A second issue relates to the statistical analysis used to compare local to nationally selected participants. The authors do not report the statistical test used determine if the groups were significantly different. Since neither group was randomly selected from a population sample it is not possible to infer the significance of the results to a larger population. The local teachers self-selected from a local school district and the national group were selected by the members of the research team. Therefore, because the teachers were not randomly selected, inferring population means is not supported by their research design (Hahs-Vaughn & Lomax, 2012). Despite these issues, the qualitative analysis performed in this investigation provides an understanding of the views teachers hold about the nature of engineering. Individual elementary teachers in this investigation held very narrow views of the nature of engineering such as not understanding that engineers must work under constraints and follow a process. While this work doesn't identify an expert view of important characteristics of the nature of engineering, it does indicate that further work needs to be done to inform elementary teachers about the nature of engineering.

Karatas, Bodner, and Unal (2015) reported a much more detailed 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 he believed were appropriate for post-secondary research. He states that the 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 he developed are "Goal-orientated design", "Tentative/Temporary", "Theory, artifact, and failure-laden", "Social and cultural", "The method", "Creativity, imagination, and 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 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.

The work by Karatas et al. (2015) on the nature of engineering provides the first attempt to enumerate features of the nature of engineering, but there are issues with its methodology. First, the development of the tenets of the nature of engineering is based on opinion and are anecdotal (Karatas, 2009, p. 32). They appear to have been based on sources that are not provided. A second methodological issue relates to the initial development of the VNOE questionnaire. Karatas (2009) provides a detailed list of tenets of the nature of engineering with literature citations to support his choices. However, when describing the development of VNOE questions, he does not describe how the questions elicit responses that would reflect student views of the tenets. For example, questions 8 and 10 (regarding the tasks of engineering and how quality engineering work can be identified) are the primary questions to probe the students' views on the nature of engineering. Most of the other questions (10) are related to concepts not related to the tenets of the nature of engineering. It is not clear how these two questions address the range of tenets. This approach (Karatas, 2009) is in contrast to the development of the views of the nature of science questionnaire (Lederman et al. 2002). In this instrument, questions were developed and tested to elucidate student thinking on specific aspects of the nature of science. A final methodological issue of the Karatas (2009) investigation was the lack of information regarding the initial validation of the VNOE instrument. Karatas (2009) described the initial process of developing questions based on various aspects of the nature of engineering. He did not fully describe how these questions became the final VNOE questionnaire. Were the questions reviewed for face validity by a panel of experts? How did the questions change after they were administered to a pilot group? What were the results of the pilot investigation and pilot interviews? Because the researchers did not provide these details, it reduced the trustworthiness of the results. Despite these issues, the Karatas et al. (2015) study provides an important first step in defining characteristics of the nature of engineering and examining views of students. Because the researchers developed a list of tenets of the nature of engineering based on opinion and literature support, it lacks empirical support that would give it a broader application.

Delphi Methodology

The Delphi methodology provides a way to develop a consensus view of the nature of engineering using rigorous, formal, data-driven methods. The following section describes the history of the method, philosophical foundations, research paradigm, and optimal uses.

The Delphi approach is a mixed-methods research tool that has a long history in the social sciences. The methodology was developed by Helmer and Dalkey (1963) at the RAND Corporation in the early 1950s for defense forecasting. The method was developed to improve the process of building a consensus among a group of experts. In the traditional consensus format, the committee, it can be difficult to gain a true consensus for a number of reasons (Helmer, 1967). First, individual personalities with perceived authority can heavily influence the decision in the biased direction. Second, it can be difficult for an individual on the committee to go against publically expressed opinions. Finally, individuals can succumb to group-think which causes the entire group to lean in a certain direction despite the evidence. The Delphi seeks to reduce the occurrence of these issues using a formal questionnaire approach. The procedure has three major features (RAND Corporation, 1969).

1. Anonymous feedback: Participants' responses are not identified, allowing them to speak their mind without fear of group reprisals.

2. Iteration: Panel members respond to the questions multiple times, allowing them to respond to feedback from other members.

3. Statistical reporting: The level of agreement on individual items is monitored using quantitative methods. The use of these methods attempts to reduce the impact of dominant participants, allows members to change their mind without social pressure, and lowers the impact of group conformity.

These features are the foundation of a methodology that supports the development of group consensus while minimizing negative group dynamics.

Research Paradigm

As a mixed-method approach, the Delphi process draws on multiple research paradigms. The Delphi approach, as typically implemented, consists of a qualitative phase followed by a quantitative phase. Each of these phases assumes a philosophical heritage and brings with it an associate worldview (Tapio, Paloniemi, Varho, & Vinnari, 2011). The philosophical leanings of the overall investigation depend on the emphasis of one phase of the investigation over the other. As described by the authors of the first Delphi approach (Dalkey & Helmer, 1963), the original approach emphasized the quantitative aspects of the investigation. The results of this investigation described numeric responses made by the participants (quantity of explosives needed to deter specific threats) and elevated these descriptions over the nuances of the opinions supporting these numbers. This approach would be an ideal Lockean Inquiry System as described by Churchman (1971). The Lockean Inquiry System relies on the epistemology espoused by John Locke and epitomized by positivism. In such a Delphi investigation, development of theory would come after collecting objective data and statistical analysis to quantify the consensus by a group of experts (Mitroff, & Turoff, 1973). The output of this approach is primarily quantitative with numerical values being the primary results. However, alternative approaches can be taken in a Delphi investigation.

The paradigm used in this dissertation emphasized the qualitative aspects of the research over the quantitative. Following a mixed-method Exploratory Design (Creswell & Plano-Clark, 2007, p. 75) this investigation began with qualitative data collection and analysis before developing a framework or taxonomy. This framework was then used to collect quantitative data that is analyzed and organized into results. The interpretation of both sets of results emphasized the qualitative phase through the use of participant feedback elicited multiple times throughout the process. Participants were provided the qualitative responses of other members of the panel to encourage members to evaluate their position in light of other member's opinions. This use of the Delphi followed more of an interpretivist approach due to its emphasis on concepts rather than numbers and its goals of using group interaction to improve understanding. In contrast to typical positivist approaches, the Delphi does not segregate responses of individual participants to ensure that cross-contamination of ideas does not occur. Instead, the Delphi attempts to develop a group feedback dynamic where the individual responses of participants are given to each respondent in the following round. The goal of this technique is to encourage cross-fertilization of ideas within the panel to further encourage consensus on specific concepts.

When approaching the Delphi using an Exploratory Design (Creswell & Plano-Clark, 2007), a constructivist paradigm may be used to describe the methodological approach to the research. Although the Delphi approach may suffer from an "Unholy Marriage" (Tapio et al., 2011) of interpretivist and positivist paradigms, focusing on the qualitative side of the approach can clarify the philosophical confusion. Hanafin and Bowles (The Irish National Children's Office, 2005) make the case that the Delphi can be seen from a constructivist paradigm. Constructivism supports a relativist ontology, which views reality as supporting multiple perspectives (Guba, 1990). The Delphi approach recognizes the results of the investigation will be one perspective of the topic based on the collective views of the panel recruited. In addition, constructivism merges the inquirer and the inquired into a single entity. Due to the subjective nature of qualitative analysis, the views of the researcher in a Delphi investigation cannot be completely divorced from the analysis. A constructivist paradigm leads to a methodology in which: "Individual constructions are elicited and refined hermeneutically"; constructions are "compared and contrasted dialectically"; and the goal is to generate a small number of constructions; "…On which there is substantial consensus" (Guba, 1990, p. 27). The Delphi mirrors this description of a constructivist methodology and uses: a) open-ended questions to elicit participant viewpoints that are coded qualitatively; b) individual viewpoints shared with participants to encourage a dialog of ideas; c) an end goal of determining a consensus among participants. While the Delphi emphasizes the use of experts who have understanding of the investigation topic, it also encourages respondents to engage in a (written) debate and change their minds based on the responses of other participants. Given the diversity of approaches to the Delphi, it is clear that not all Delphi studies use a constructivist paradigm. Some studies emphasize the numeric and statistical side of the mixed-method. The approach taken in this dissertation, however, is of a constructivist position that emphasizes the consensus of individual views on the topic.

Types of Delphi Studies

Perhaps due to differing research paradigms and lack of definitive empirical studies on the technique, Delphi approaches exhibit a wide range of methodological implementations. The Delphi is characterized by three unique features: Anonymous group communication, multiple iterations and statistical analysis of results (Osborne et al., 2003). Beyond these common characteristics, there has been wide variation in approach. Studies differ on initial round type (literature review or participant survey), number of rounds (one to five), method of feedback after each round (anonymous or named), and measures of consensus (Hasson & Keeney, 2011). Hasson and Keeney identified ten types of Delphi designs. Researchers Okoli and Pawlowski (2004) distil the list down to two major types for educational use: Forecasting / issue identification and Concept / framework development. The Forecasting / issue identification Delphi emphasizes the development facts about events that have not yet occurred and the Concept / framework development Delphi attempts to identify important concepts or knowledge for curriculum use. For this dissertation investigation, a concept development Delphi is used to identify key aspects of the nature of engineering and rank them by importance for use in K-12 education. This approach has been followed by a number of curricular Delphi studies.

The Delphi has been recommended for developing curriculum since the early days of Delphi research. Judd (1972) noted the Delphi methodology had been used in a number of higher education situations, including curriculum development. Reeves and Jauch (1978) made the case for using Delphi in curriculum development because it was a more rational approach than traditional curriculum development techniques. The Delphi has been used to develop physics curriculum (Haussler & Hoffmann, 2000), agricultural education (Akers, Vaughn, & Lockaby, 2001), information systems (Bacon & Fitzgerald, 2001), nursing (Barton, Armstrong, Preheim, Gelmon, & Andrus, 2009), engineering education (Childress & Rhodes, 2006; Dearing, & Daugherty, 2004), science education (Bolte & Schulte, 2013; Osborne et al., 2003; Post, Rannikmäe, & Holbrook, 2011) and science teacher education (Kloser, 2014). The standard approach used in a majority of these studies has been a three-round concept / framework development Delphi. Round 1 (Concept Discovery) allows panelists to propose any curricular idea they think would be appropriate to include in the final list. Round 2 (Concept Prioritization) gives participants the opportunity to determine which curricular ideas are most important from a long list of ideas. Round 3 (Concept Rating) asks panelists to verify the importance of each concepts after reviewing comments from other panelists. This final rating also determines the rank-ordered list of curricular concepts from most important to least important.

Although the Delphi was originally developed as a forecasting tool (Dalkey & Helmer, 1963), it has been used to develop curricula for over forty years. One of the reasons the Delphi works well for curriculum development is that a curriculum is a codification of concepts that students will need to know in the future (Clayton, 1997). Instead of developing the set of knowledge that students need to know using the opinion of a small group of experts, the Delphi brings a rigorous, data-driven approach to the often-messy process of developing curriculum and gaining consensus for stakeholders. Thus, for newly developing fields, such as K-12 engineering education, the Delphi is a way to build a framework of knowledge by supporting the development of consensus among a group of experts.

Although some researchers have criticized the Delphi (Davidson, 2013; Paré, Cameron, Poba-Nzaou, & Templier, 2013) it has been widely used in both PhD theses and general research (Landeta, 2006). One criticism has been that researcher bias can influence the development of themes after the brainstorming phase (round one) of the method. Paré et al., (2013) note that this issue can be reduced if participants are allowed to add items from the original list and make comments about the development of individual themes. Another criticism is that the Delphi participants are often a sample of convenience and do not reflect expertise in the field. This problem can be addressed by clearly defining qualifications required for participation in the investigation beforehand (Paré et al., 2013). Finally, Hasson et al. (2011) identifies many of the criticisms as stemming from attempts to present the results as primarily quantitative, reporting traditional reliability and validity measures. Since the selection of participants is not a random population sample, inferential statistics are not recommended in Delphi studies. Instead, Hasson et al. (2011) recommends treating Delphi results as qualitative by developing methods that indicate trustworthiness and credibility. The present investigation will approach the work from a qualitative stance and report descriptive statistics only.

Summary

After reviewing the literature cited above on the nature of engineering for K-12 students, it is clear that a consensus does not yet exist in the interdisciplinary field of engineering education. National efforts to improve STEM education in the United States have begun to emphasize the inclusion of engineering in all science and technology classes at the K-12 level. This push to improve the engineering literacy of students requires a clear understanding of what students should know about engineering as a field. In the more developed field of science education, researchers have called for students to understand a three-fold view of the field to develop scientific literacy: Science knowledge, science processes and practices, and science epistemology (Specter & Lederman, 1990). Recently the ASEE (2014a) and Pleasants et al. (2016) have articulated a similar approach to K-12 engineering education. They call for students to learn: Engineering content knowledge, the practices of engineering, and the nature of engineering in order to understand the field. To date, effort has been made to outline the first two areas. Researchers have outlined the content that K-12 student should know through a series of Delphi studies (Childress & Rhodes, 2006; Childress & Sanders, 2007; Dearing & Daugherty, 2004; Daugherty & Mayer, 2010; Moore et. al., 2014). Researchers such as Smith (2006) have conducted Delphi studies on what students should understand about engineering design, and the Next Generation Science Standards (NGSS Lead States, 2013) provides guidance regarding teaching engineering practices for K-12 educators. However, the topic of the nature of engineering has not been explored in great depth.

A limited amount of research has been conducted on aspects of K-12 nature of engineering. A few studies (Lachapelle, Cunningham, Lindgren-Streicher et al., 2006; Lambert et al., 2007) have looked at the view of teachers on the nature of engineering. These studies provide a perspective on teachers' understanding of engineering as a field, but do not attempt to explore the concepts that would be important for K-12 students to learn. What is clear from these studies is that teachers some teachers possess misunderstandings about the field of engineering. Karatas et al. (2015) undertook an ambitious project to develop a set of tenets of the nature of engineering via a literature review and examine the views of first year undergraduate engineering students. This work is an important first step in defining potential concepts for student to understand about the nature of engineering, but the list of concepts was not developed in a data-driven manner.

Efforts have also been made in philosophy to define the nature of engineering knowledge from an epistemological viewpoint. Two major views of the epistemology have been proposed. Some philosophers view the field of engineering as integrating multiple fields each with their own epistemology (Figueiredo, 2008; Gibbons et al, 1994). Other philosophers have proposed a unified epistemology of engineering based on pragmatism (Goldman, 2004). Despite these efforts, there does not appear to be a consensus on which approach is best suited for the field. Even if there were a consensus on a unified epistemology of engineering, K-12 teachers would not be able to use this understanding to develop curriculum for their classrooms. Philosophical approaches are developed with philosophers as the audience, and K-12 teachers and curriculum developers typically do not have the required background to understand and implement these concepts.

What is needed to move the field of engineering education forwards is to develop the nature of engineering at a level that is appropriate to K-12 education. Various approaches to the nature of engineering have been taken, but none have provided a rigorous, formal, data-driven approach to identifying important aspects of the nature of engineering for student to learn. The Delphi provides a way to develop forward-looking ideas for curriculum development that sidesteps some of the pitfalls of earlier research. First, rather than relying on the opinion of the researchers in developing curricular concepts, the Delphi relies on a diverse group of experts who understand the problem. Second, the Delphi allows a large group of panelists to explore ideas and debate their merits at a distance. This allows a nationally representative group of experts to come to a consensus on the components of curriculum that are most important. Finally, a Delphi investigation helps the expert panel to narrow the list of potential concepts and prioritize the list for easy use. The output of such an investigation would be useful for future research, policy creation, curriculum development, and classroom use. This rigorous approach to understanding the nature of engineering will bring needed clarity to the field of K-12 engineering education.

Table 1

Tenets of the Nature of Science, K-12 Level (Lederman et al., 2002)

Nature of scientific theories Scientific knowledge is always subject to change and improvement
The empirical nature of science Understanding the difference between observation and inference
The Theory-Laden Nature of Scientific Knowledge Theoretical perspectives of scientists influence their observations
The Social and Cultural Embeddedness of Scientific Knowledge Science is practiced in a larger culture which influences its evolution
The Creative and Imaginative Nature of Scientific Knowledge Science requires leaps of creative insight to explain phenomena
Inference and theoretical entities in science Understanding the difference between observations and inferences
The Myth of the Scientific Method Science does not rely on a recipe that is applied in all situations
Distinctions and relationship Between Scientific Theories and Laws Understanding the difference between theories and laws

Table 2

Nature of Science Concepts Addressed in Key Literature in the Development of VNOS[1]

Nature of Science concept	Lederman et al. (1990) VNOS-A	Abd-el-Khalick et al. (1998a) VNOS-B	Abd-el-Khalick et al. (1998b) VNOS-C	Lederman et al. (2002) Overview
Tentativeness in science	Present	Present	Present	Present
Theory-laden		Present	Present	Present
Observation vs. Inference		Present	Present	Present
Creative and imaginative		Present	Present	Present
Empirical		Present	Present	Present
Social and cultural embeddedness			Present	Present
Theories vs. laws			Present	Present

[1]Views of the Nature of Science questionnaire (Lederman et al., 2002)

Table 3

Related Nature of Science Concepts Based on Two Approaches

Lederman et al., (2002)	Osborne et al. (2003)
The empirical NOS	Scientific method and critical testing
Inference and theoretical entities in science	Hypothesis and prediction
Nature of scientific theories	Science and questioning
Distinctions and relationship between theories and laws	
The creative and imaginative NOS	Creativity
The theory-laden NOS	Science and certainty
Social and cultural influences on scientific knowledge	Diversity of scientific thinking

CHAPTER 3 -- METHODS

Overview

The methodology employed for this research was the three-round Delphi investigation first described by Helmer and Rescher (1959). The Delphi is a semi-structured mixed methods approach that consists of one qualitative round followed by two or more quantitative rounds. The Delphi 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 methodology because it has been used extensively in curriculum studies (Bolte, 2008; Kloser, 2014; Osborne et al., 2003). 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 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

(Delbecq, van de Ven, & Gustafson, 1975). 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 utilizes written communication, responses are more likely to be reasoned and thoughtful because the participants have time to compose their responses (Akins, Tolson, & Cole, 2005). Written communication also allows researchers to capture a record of the communication between participants for further analysis. These advantages make the Delphi an ideal methodology for use in a curriculum investigation.

Along with the benefits the Delphi brings to a research investigation come some challenges that must be overcome to ensure a successful outcome of the research. One of the main disadvantages with the technique is the amount of elapsed time it takes to complete all three rounds (Gordon, 2009). Given the time it takes for participants to respond to the survey, analysis of results, and the development of a new survey, each round can easily take a month. Given an initial invitation survey and three rounds, a full Delphi investigation can take upwards of four months from invitation to final results. The present investigation endeavored to reduce the time between rounds through a number of efforts. First, the investigation was conducted using email to eliminate the time to deliver a mail survey, which could have been up to a week for each round given the broad geographical distribution of respondents. Second, an adequate number of participants were recruited to the survey so that the survey would have enough participants at the end of the survey. This allowed the researcher to close the survey at precisely two weeks rather than waiting for more participants to complete the survey. While closing the survey after a predetermined amount of time had the potential to increase the number of participants completing the entire set of surveys (due to shorter length), it also had the possibility of reducing the number of respondents that completed the first survey. Emphasis was placed on reducing the elapsed length of the surveys instead of completion of individual rounds to ensure that the largest number of participants completed all rounds. Finally, the analysis and development time for the second-round survey was minimized by the use of qualitative coding software (Nvivo, 2015). In addition, a blanket institutional review board (IRB) approval of the entire investigation was obtained in advance. This allowed for rapid coding of participant responses, and rapid deployment of the next survey without waiting for IRB approval of the survey for each Round. These efforts were undertaken to reduce participant attrition by reducing the elapsed time for the survey.

The goal of the Delphi is to develop a consensus from a group of experts that is manifested in consistent ratings from round to round. The Delphi literature shows that more than 15 metrics have been used to determine consensus (Von der Gracht, 2012). These metrics include straightforward approaches such as number of rounds, subjective analysis, and a certain level of agreement. In addition, some researchers have used more complex measures such as average percentage of majority opinions, standard deviation, interquartile range and inferential statistics. A majority of Delphi studies use level of agreement as a measure of consensus (Powell, 2003). This measure has also been used extensively in education as in Osborne (2003), Bolte

(2013), and This investigation will define consensus as an agreement of opinions in the group. Stability is the consistency of theme ratings between rounds. When a theme shows high stability, further changes in responses on an item are unlikely (Dajani & Sincoff, 1979). This present investigation employed two qualitative rounds to reduce participant fatigue (Walker & Selfe, 2015). Therefore, stability of group responses on individual items were determined by comparing the response distribution (participants changing their rating) between Rounds 2 and 3 to determine which aspects meet these criteria. In order to ensure the most robust results, only aspects that achieve both consensus and stability were used in the final results.

There appears to be no agreement as to the optimum number of participants in a Delphi investigation (Akins et al., 2005). Studies have been conducted with any number of panel members. A majority of studies report panel sizes between 7 and 30 (Paré et al., 2013). Hogarth (1978) provides empirical data to recommend that Delphi panels of 8 to 12 members are optimum under a wide range of situations. Although panel sizes less than 30 are often used in Delphi investigations, larger panels have been used in a number of studies. Haussler and Hoffmann (2000) completed a Delphi curriculum investigation with 73 experts while Connors (1998) surveyed 82 agricultural educators. Bolte has also completed Delphi investigations with large numbers of participants as high as 446 (Bolte, 2008) and 2,400 (Bolte & Schulte, 2013). For Delphi studies that have larger than 30 participants, only marginal improvements in reliability are seen and it can be more difficult to reach consensus (Hogarth, 1978). For this present investigation, the goal was to retain approximately

30 participants at the end of the investigation. Due to attrition, a larger number of participants were recruited to begin the survey process to yield 30 participants at the end of Round 3.

The selection of the participants is of utmost importance in a Delphi investigation and in the present study because it is important to ensure they understand the field of education and come from varied backgrounds (Paré et al., 2013). Rather than randomly sampling a population under investigation, the Delphi recommends purposive selection of individuals that meet specific criteria for expertise (Clayton, 1997). For the present investigation participants were recruited based on their involvement in national education associations and candidates were recruited that meet the criteria listed in Table 4.

Initial Invitation

Participants were recruited from the following categories: K-12 science teachers, K-12 engineering teachers, science education faculty (post-secondary) and engineering education faculty (post-secondary). Each group was chosen to represent a unique perspective on K-12 engineering education. K-12 engineering teachers teach engineering in stand-alone courses to prepare students for future careers in engineering. K-12 science teachers have been asked by state and national standards bodies to include engineering in their classes to provide applications of science concepts and increase interest in the field of engineering (NRC, 2011. University engineering education faculty conduct research and engage in outreach activities that will prepare students to enter engineering programs. University science education faculty prepare pre-service teachers to teach engineering in K-12 science courses.

The goal was to recruit similar proportions from each participant group. Potential candidates were recruited through their involvement in professional associations. K-12 engineering teachers were recruited based on their membership in ITEEA. Members were included if they resided in the states of Alabama, Connecticut, Delaware, Idaho, Maryland, Missouri, North Dakota, New Hampshire, New Jersey, and Utah. These states were chosen because they have been identified as having explicit engineering standards in the state curriculum (Carr et al., 2012). K-12 science teachers were recruited based if they had made a presentation at either state, regional, or national meetings of the National Science Teacher Association (NSTA). Engineering education faculty 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. Science education faculty were recruited based on their membership in the National Association for Research in Science Teaching. A recruitment letter (See Appendix A) was sent to association email lists as outlines above. Since the Delphi method is typically conducted on groups smaller than 30 individuals (Paré et al., 2013), the present study randomly selected 100 participants from the qualified pool of respondents. This was to ensure that at least 30 participants completed all three rounds of the Delphi process. Although participants were not stratified by state in the selection process, the final list of participants represented a broad geographic distribution across the United State.

Recruitment emails were sent to the email lists in November, 2015 and participants were given two weeks to respond. Email reminders were sent one week and one day prior to the close deadline. Due to the overwhelming response rate from the initial invitation (See Appendix B), participants were randomly selected to participate in the Delphi investigation. In order to ensure participants had an understanding of K-12 engineering education, only respondents with the following background were qualified for the study: Appropriate education, involvement in K-12 engineering teaching or research, and use K-12 engineering concepts in classes that they teach. Of the 610 participants who responded the initial invitation, 428 were qualified based on these characteristics. 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 next questionnaire (see Table 5).

Round 1

The first step of the Delphi was to determine all the nature of engineering aspects that participants viewed as important for K-12 education. The Round 1 questionnaire consisted of one open-ended question panel members were sent via an email link. Participants were asked to "List all the characteristics of the nature of engineering concepts 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, thus reducing bias.

The Round 1 questionnaire (See Appendix A) was sent in December 2015 using the Qualtrics Online Survey Software (2016) and participants were given two weeks to respond. Because the survey was electronically closed after the two-week window expired, it is not known whether additional respondents would have completed the survey if given more time. None of the non-responding potential participants contacted the researcher requesting to take the survey at a later date. Reminders were sent one week and one day before the questionnaire close date. A total of 65 participants responded to the questionnaire (see Table 5). In addition, Table 6 shows the distribution of participant grade-level focus in K-12 education among those who completed Round 1. The distribution of participants completing Round 1 was chosen because a majority of these participants completed Rounds 2 and 3. Approximately half of the participants worked at the high school level (51%) with about a quarter each working at the elementary (23%) and middle school (25%) level. Table 7 shows the gender distribution of the panel completing Round 1. Gender was determined by conducting Internet searches for public information available on school web sites for each participant. Approximately equal numbers of panel members were male (52%) as female (48%). The gender distribution for Round 1 was used as the basis for gender analysis because a majority of these participants (92%) finished Round 3 as well.

A list of nature of engineering aspects was developed from the participant responses by coded each item using open-coding and axial coding techniques as 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 from the participant responses. Each sentence was evaluated for concepts related to the nature of engineering and labeled. Axial coding is the second step of the Grounded Theory methodology and is the process of identifying relationships between the items coded in open coding. A first round of coding was completed with a second researcher using the Nvivo (2015) software. One-third of the responses 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 aspects remained. Each aspect was given a title and a summary sentence to be used in subsequent rounds. The title and summary sentence were modified after each round to reflect comments made by participants. Table 8 shows each aspect 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.

<u>Round 2</u>

The Round 2 questionnaire (See Appendix A) gave participants the opportunity to review the aspects developed from Round 1 and to rate each aspect on a five-point Likert-type scale (1= Not Important, 2=Slightly Important, 3=Moderately Important, 4=Important, and 5=Very Important). The goal of this round was to reduce the total number of aspects to the items participants viewed as most important. The Round 2 questionnaire was sent to participants January in 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. The participants were asked to evaluate each item for its important to a K-12 curriculum. Participants were able to justify the rating they gave so 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 aspect list. This process narrowed down the aspect list so that only the most important items were taken to the next questionnaire.

Of the 65 participants that completed Round 1, 63 completed Round 2 (See Table 5). 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 18 aspects 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 aspects had some degree of consensus from the outset.

Round 3

The third Delphi survey 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 aspect along with mean, standard deviation, and percent rating greater than or equal to 4 (important or very important). Based on comments from participants, two aspects were combined: The *User Focused* aspect was merged into the *Contextual* aspect. 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 required three responses (rating, justification, and comments), a survey utilizing all aspects from Round 2 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 greater than or equal to 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 aspects not taken into Round 3 were: *Accessible*, *Inclusive of Multiple Disciplines*, and *Historical*.

The Round 3 questionnaire was sent to participants in January 2016 and participants were given two weeks to submit their results (See Appendix A). 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 Delphi 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 aspects.

Final Questionnaire

A concluding questionnaire was set to all participants who completed Round 3. The goal of this questionnaire was to allow participants to define the term 'Nature of Engineering' and to recommend the appropriate grade-level to introduce each nature of engineering concept in school. To define 'nature of engineering' participants responded to an open-ended question about the meaning of the term. To identify the optimum grade-level for the introduction of each nature of engineering concept, panelists were asked to choose the appropriate grade-level from a list (from K-12). The questionnaire was sent to participants May 2016. Participants were given two weeks to respond to the questionnaire and reminders were sent one week and one day prior to the close date. A total of 52 participants completed the questions of the 60 participants from Round 3. Responses to the nature of engineering question were analyzed qualitatively using open coding as described above. Responses to the appropriate grade-level for introducing each nature of engineering aspect were analyzed using descriptive statistics such as mean and standard deviation. Panelists participating in this final questionnaire had a unique perspective on the nature of engineering because they had been part of all three Delphi rounds and had the opportunity to respond the ideas presented by other panelists. This questionnaire also provided an opportunity for participants to view the final list of nature of engineering aspects and provide final feedback regarding wording of the description.

Consensus and Stability

Researchers using the Delphi 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 aspect from one round to the next. For this investigation, consensus was defined as minimum of 75% of participants rating an aspect 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 Rounds 2 and 3 as defined by Scheibe, Skutsh, and 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 aspects would appear to be stable when in-fact large changes have occurred between rounds. In order to determine how many participants changed their ratings between rounds, the difference between number of participants selecting each point on the scale (1 to 5) is calculated for Rounds 2 and 3. Summing the absolute value of this number and dividing by 2 gives the total number changes for the group (because a single change from one point on the scale to another two points of difference). This total is divided by the number of participants completing the survey to yield the percent of participants who changed their answer between rounds. The final results presented in this investigation are the aspects that achieved both stability (as calculated above) and consensus between Rounds 2 and 3. It is not known whether additional rounds would have increased the number of items achieving stability, but the number of rounds was limited to three in advance to reduce participant fatigue.

Table 4

Expert Selection Criteria for Delphi Investigation

Criterion	Teachers (K-12)	Faculty (Post-secondary)
Education	Professional development in engineering education	PhD in science, science education, engineering, or engineering education
Teaching / research background	Taught three or more years	Research in K-12 engineering
		--Or--
K-12 Engineering in practice	Includes engineering concepts in classes taught	Includes K-12 engineering in courses taught

Table 5

Participants Completing Each Delphi Round by Group

Group	Responded	Qualified	Selected	Round 1	Round 2	Round 3	Final
Engineering teachers	125	112	25	18	18	17	12
Science teachers	178	121	25	15	14	14	12
Engineering education faculty	136	99	25	15	14	12	12
Science education faculty	171	96	25	17	17	17	16
Total	610	428	100	65	63	60	52

Table 6

Primary Grade-level Focus for Expert Panel Members Completing Round 1

Panel	n	K-5		6-8		9-12	
Engineering teachers	18	5	(28%)	2	(11%)	11	(61%)
Science teachers	15	3	(20%)	6	(40%)	6	(40%)
Engineering education faculty	15	2	(15%)	6	(40%)	7	(47%)
Science education faculty	17	5	(29%)	3	(18%)	9	(53%)
Total	65	15	(23%)	17	(26%)	33	(51%)

Table 7

Expert Panel Gender Distribution for Expert Panel Members Completing Round 1

Panel	n	Female	Male
Engineering teachers	18	7 (39%)	11 (61%)
Science teachers	15	9 (60%)	6 (40%)
Engineering education faculty	15	7 (47%)	8 (53%)
Science education faculty	17	11 (65%)	6 (35%)
Total	65	34 (52%)	31 (48%)

Figure 1

Example Survey Item from Rounds 2 and 3 Surveys

Problem Focused

Concept:
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.

Results

Mean: 4.62

Standard Deviation: 0.58

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

Summary of comments

One respondent does not agree with the word "perceived" in the theme statement.

The idea that engineering is to improve the quality of life for people should be included.

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.

CHAPTER 4 -- RESULTS

The results for the present investigation are reported in the order of the four surveys that were administered. The Round 1 section describes the list of concepts that participants nominated for inclusion in the final list of aspects. Under the Round 2 heading is a listing of the ratings of the Round 1 aspects of the nature of engineering provided by panel members along the cut-off rule used to narrow the results. Third, the results of the Round 3 survey describe the final ratings and descriptions of the aspects. An analysis of the differences in group responses are also included in section three. Fourth, the results of the definition of the nature of engineering and age level to introduce each aspect are included.

Round 1

Results from Round 1 were aspects generated by the qualitative coding process. After open coding the raw participant responses, a total of 499 individual nature of engineering aspects were identified. Participants made reference to three standards documents and one publication they believed provided useful concepts for the nature of K-12 engineering (ASEE, 2014a; Moore et al., 2014; National Academy of Engineering & National Research Council, 2009; NGSS Lead States, 2013). Aspects of the nature of engineering from these documents were added to the list of items provided by panel members. Relationships were identified between many of the aspects after completing the axial coding process yielding a total of 18 aspects. The first column of Table 6 shows the nature of engineering aspect and summary statement developed (note minor wording changes were made to each aspect after Round 2 and 3 based on participant suggestions).

Round 2

Participants rated each item on a Likert-type scale in Round 2 as well as providing a justification for their ratings. Of the 18 aspects in the survey, the top four (by importance rating) were *Problem-oriented* (4.62), *Design-Driven* (4.54), *Constrained by Criteria* (4.52), and *Collaborative* (4.52). These aspects also showed a relatively low standard deviation (ranging from 0.58 to 0.78) indicating that agreement was beginning to form. In addition, participants rated these items above 4 (important or very important) in high numbers (ranging from 89% to 95%). The bottom three items did not show such high ratings. The aspects *Inclusive of Multiple Disciplines*, *Accessible* and *Historical* all had low ratings (at or below 65%). In addition, these items also had modes that were lower than 5 (1=not important to 5=very important). These items also all had standard deviations greater than 1.00 indicating a low level of agreement. After analysis of all the aspects in Round 2, these three items were removed from the list for the next round. These items were below the cut-off rule defined in the methods section as having a mean greater than 4.0 and / or a mode greater than 5. At the conclusion of the Round 2 analysis, 15 aspects were moved to the next round for evaluation.

Round 3

The analysis of Round 3 results yielded eight aspects met the requirements of being both stable and achieving consensus. As noted above, stability was defined as a distribution change of less than 15% between Rounds 2 and 3 and consensus was defined as 75% of participants rating an item as important or very important. The aspects (shown in Table 6) include: *Divergent, Creative, Iterative, Model-driven, Communicative, Constrained by Criteria, Collaborative, and A Unique Way of Knowing*. Most of the aspects in Round 3 showed high levels of consensus (greater than 85% rating 4 or above) except for the aspects: *Problem-oriented and Develops Products, Processes, and Protocols* (with 67% and 73% rating above 4, respectively). Of the aspects with high consensus, the most stable were; Divergent, *Creative, Iterative, and Communicative, and A Unique Way of Knowing* (with 10% or greater stability). The aspects, *Model-driven*, *Constrained by Criteria*, and Collaborative were less stable but had stability between 11% and 15%. The remaining items (*Holistic, Design-Driven, Multidisciplinary, Ethical, and Contextual*) had the least stable results with values ranging from 16% to 23%.

Panel members were encouraged to make comments on each aspect in both Rounds 2 and 3. In addition, they were asked to justify their position on Round 3 if they were more than 1 point away from the panel mean in Round 2. Following are comments made on the final list of aspects by participants in both rounds. Panel members made more than double the comments in Round 3 (8,788 words) compared to Round 2 (3,751 words), indicating that they were engaged with the topic and responding to comments from the previous round.

Divergent. Participants gave the highest rating to the *Divergent* aspect on Round 3, but ranked it as the third most important aspect in Round 2. Participants saw this aspect as being quite different than the typical school approach where one answer is correct. One participant said, “I think this is one of the most important aspects of teaching engineering to students or other educators.” Another participant stated that “This is pretty revolutionary compared to traditional instructional models of math, science, and engineering.” Some participants noted that this item is similar to the second aspect, *Creative*. Creativity is required to develop multiple solutions to a problem. They saw the *Divergent* aspect as being important because it highlights the concept that there are usually multiple ways to solve an engineering problem. Students are so used to looking for the one ‘right’ answer, that understanding that divergent becomes a key component of the nature of engineering to be taught to K-12 students.

Problem-oriented. While the *Divergent* aspect was ranked highest in Round 3, *Problem-oriented* was ranked highest in Round 2. Not only did the aspect drop from the top of the list in Round 3, but it also was rated as the last item on the list with only 67% rating it higher than 4 (important or very important) and a stability of 31%. This dramatic change is reflected in the large number of comments given by participants in Round 3 in response to their colleagues’ justifications in Round 2. Participants were given the following summary of comments from Round 2:

- The idea that engineering is to improve the quality of life for people should be included.

- This statement paints a falsely positive view of engineering as working toward the public good. Most engineering is conducted with a profit motive. That is not evil, that is just the way it is.
- 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.

As worded in Round 2, the aspect statement described engineering as meeting needs and wants with profit being a goal for some engineering organizations. Participants responded to this statement and to panelist comments in Round 2 by pointing out that the statement did not include all types of engineering. One participant noted, "…some engineers (i.e. civil engineers) are not designing products to sell to customers for a profit. This statement is misleading." Another panelist focused the public good aspects of engineering by stating; "The second part does not apply to many types of engineering that are oriented toward public good (e.g., civil infrastructure, clean air and water etc.) In fact, I think that distorts the range of the value of engineering work." This comment was echoed by other participants who saw this view of engineering as "…presenting a cynical view of life to K-12 students" and that "Engineering in K-12 should focus on social good, not profit generation." Other panelist's saw this concept as being covered by other aspects and not distinct enough to warrant its own item. Some also saw the profit motive as not being important for K-12 students to learn. In the end, these views provide some insight into why the aspect dropped to the lowest rating item in Round 3 and as to why many participants may have changed their views between Rounds 2 and 3.

Design-Driven. The second highest rated aspect from Round 2, *Design-Driven*, also did not make it onto the final list due to high amount of change (23%) between rounds, indicating low stability. Some insight into this change is reflected in a comment made by a participant in Round 2 that was provided on the Round 3 survey. The participant stated that “The engineering design process reminds me of the Scientific Method. [I am] not a fan.” This thinking was elaborated with Round 3 comments such as, “I also fear that teachers love processes that have steps, and this could work its way into classrooms and put new life into the scientific ‘method’ that we've worked so hard to eliminate.” A number of participants made reference to the fear that a process or steps labeled as the “Engineering Design Process” would become “THE” one and only design method. One participant who had worked as an engineer commented, “Let's investigate and interview engineers and find out if they have a method. Perhaps many do. I never did. It never crossed my mind that there was a method to what I was doing. Sure, I designed something and then tested a prototype or FEA design, and modified it, but sometimes I did backwards design, or de-construction to determine methods, and the method was entirely intuitive, not proscriptive.” This wasn’t the only perspective, however. Some participants, who identified themselves as K-12 teachers, viewed the engineering design process as a way to provide structure for students so that they have a basic framework to guide their work on engineering projects. One K-12 teacher stated, “Following the engineering design process IS what we want students to learn so that they get comfortable with the process of solving problems by using a systematic approach." In the end, almost a quarter of the respondents (23%) changed their responses between Rounds 2 and 3 removing this item from the list of aspects that showed high consensus and stability.

Creative. Participants rated *Creative* as the second most important aspect of the nature of engineering (See Table 6). Panelists saw engineering as involving both creativity and logical thinking at different times in the problem solving process. Although participants did not see creativity as a unique aspect of engineering (e.g. writing is creative, art is creative, science is creative) they saw it as an "…overlooked skill in science and engineering." People do not often think of these disciplines as being creative, but some participants thought otherwise. One participant described creativity as "…essential in order to see the multiple perspectives necessary to solve difficult problems." They saw creativity as "absolutely necessary" to solving problems because there are no cookbooks for how to solve new challenges. While a large majority of participants agreed with this aspect, some saw it as being too difficult to teach to younger students -- perhaps something that might encourage a kind of unbridled experimentation that leads to failed designs. This is why logical thinking was included in many of the comments in conjunction to creativity. Panelists saw creativity as being most valuable when it was paired with logical thinking to ensure the ideas were in line with scientific principles and historical engineering designs.

This aspect is a good example of one that received a high level of consensus as well as being one of the most stable aspects between Rounds 2 and 3.

Iterative. The aspect *Iterative* is also an example of a aspect that demonstrated very little change in rating distribution between Round 2 and 3. Some participants viewed this aspect as particularly important to the K-12 classroom because failure is discouraged in many traditional classrooms. Students are often encouraged to look for the right answer while minimizing their chance of failure. In the engineering design process, a number of participants saw students building low-risk models that allow them to identify failures before building larger designs. It is important to note that many panels weren't supportive of the idea of building designs that would fail after launch. One panelist noted that "[An engineer] wouldn't expect bridge that is built to fail." Instead, a number of participants focused the optimization that accompanies problem solving. One participant summed it up by saying; "Engineers often work through many iterations of a design through prototyping, expecting that the first design may change many times before the final design is reached." Some participants noted that learning from failure is very uncomfortable for K-12 students and that students need to be taught that engineers do not always get it right the first time. A number of panelists also thought that this aspect was a very important concept for engineering, and indeed it was rated highly (as important or very important) by 92% of respondents.

Model-driven. The aspect *Model-driven* had a high degree of consensus (97% rating important or very important), but showed less stability than the other top-rated items (12% of participants changing ratings) between Rounds 2 and 3. The concept of modeling was described by participants as a way of developing an understanding of a design without building a full-scale product. Modeling was seen by many to include mathematical models, visual models (e.g. 2-D or 3-D drawings) as well as physical prototypes or mock-ups of the final item. One participant saw this as being very important because "Models to inform design decisions are unique and essential to K-12 Engineering Education." The concept of modeling (mental conceptions, drawing and building mock-ups), while not unique to engineering, was seen by some participants to be a majority of what K-12 students do in engineering activities. Despite its importance, some participants saw modeling as being a challenging concept to teach to K-12 students. One participant noted that "Students have a simple view of models which might interfere with understanding this item." Other panelists highlighted that models are often misunderstood in general by K-12 students, especially when it comes to climate science. So, while a majority of panelists viewed this concept to be important, they pointed out the effort that it will take to help students understand the concept of modeling from a deeper perspective.

Communicative. Along with the aspect of *Creativity*, the aspect *Communicative* was seen by participants as important, though it is not unique to engineering. One participant stated "…collaboration, creativity, and communication -- are critically important to most ANY job in the workforce today." Communication was seen from two perspectives, communication with colleagues and communication with stakeholders. Some participants saw the communication between team members to be similar enough to the aspect of Collaboration, that is need not be included as a separate aspect. Despite this disagreement, most participants argued that communication was important enough to K-12 engineering to be included in the final list. One engineering education faculty member stated, “I still get too many students who do NOT think engineers need to be able to write and communicate about their work in a logical and concise fashion.” Another participant highlighted the importance of being able to argue a particular viewpoint from evidence by stating,

…more importantly is the ability to communicate and justify the decisions made along the engineering design process. To be able to give evidence and reasoning for why a particular solution is optimal means students must engage in reflection and evaluation of the criteria.

Other panel members noted that engineering communication, especially in written form, is different than other types of communication. They saw communicating their technical work in a logical and concise fashion as being different from the type of writing done in history or English classes. Engineering communication in its many forms is clearly seen as an important aspect to teach K-12 students as it was rated as important or very important by 93% of respondents and showed a high level of stability, with only 8% of participants changing their rating between Rounds 2 and 3.

Constrained by Criteria. The aspect *Constrained by Criteria* was seen as a unique concept to engineering. One panelist stated, “I think this is one of the unique characteristics that engineering is different from science or other disciplines.”

Participants saw this aspect as distinguishing engineering from tinkering. If students build a solution to a problem but never evaluate it against constraints or criteria they are simply playing with materials, tinkering, or “hacking.” One participant noted “This is one unique feature of engineering that isn't always at the heart of pure science research.” The goal of science is to increase knowledge about the natural world. The goal of engineering is to design a solution to a problem. In this context, participants viewed the process of evaluating a design against Constrained by Criteria as a way to encourage students to think about engineering as developing solutions that really solve problems. This is contrasted with developing a technical design because it is technically feasible. In addition, evaluating a design against Constrained by Criteria was seen by some as a way to highlight the social responsibilities of engineering. If students understand that their designs need to be evaluated against environmental and social criteria, the engineer can be part of ensuring that engineers bear some ethical responsibilities in the work they do. The aspect *Constrained by Criteria* encompasses a large number of perspectives including costs, profitability, regulations, and social concerns. By showing consensus (95% of participants rated it as important or very important) and stability (11% of participants changed their rating between Rounds 2 and 3) panelists identified this item as important to understanding the nature of engineering for K-12 students.

Collaborative. The aspect *Collaborative* was the second-to lowest rated item with a mean of 4.40 on a 5 point Likert-type scale. Although participants saw this aspect as not being unique to engineering, they emphasized that it was an important part of the nature of engineering. One participant noted they ranked this concept lower because it was not unique to engineering. Some panel members saw K-12 engineering as the perfect context to teach collaboration in ways that could be difficult in other classes. Engineering may require some solitary work, but a majority of engineering projects require a team that has to work together. Because many K-12 engineering tasks also require students to work closely together to solve problems, students can learn the skills of working as a team. One participant noted "…one of the great benefits of teaching engineering design [is that] these skills are transferrable to many other disciplines and situations." Other participants viewed the skill of collaboration as an important skill to master regardless of the career they choose. One participant made the case for inclusion on the list by saying "While collaboration may not be unique to engineering, it is central to the problem solving process and therefore deserves to be highlighted as a theme." While this aspect was the next-to-last item in the final rating, it still was rated as important or very important by 87% of respondents. It also had a 13% change in ratings between Rounds 2 and 3, showing a modest degree of stability. As participants noted multiple times, collaboration is critical to engineering problem solving and being important to other careers should not make it less important.

A Unique Way of Knowing. The lowest rated aspect on the final list is *A Unique Way of Knowing*. In Round 2, this aspect elicited a large number of comments from the panelists. Some participants view engineering as being only an applied science. Other participants saw engineering as a fundamental field that had a longer history than science. Engineering, in their view, was connected to science in a way that would preclude having one without the other. After viewing these comments on the Round 2 survey, participants gave it a rating of 4.27 (on a five-point Likert-type scale) and 85% rated it as important or very important. With a change of 10% between Rounds 2 and 3, this item met the criteria for stability and consensus. The participants saw engineering as having its own unique characteristics that made it distinct from science. One participant viewed the goals of engineering as developing solutions, whereas the goal of science is trying to understand phenomena in the natural world. Another participant pointed out that engineers "…sometimes conduct scientific investigations to answer questions that come up in the process." Other participants did not see the value of including this aspect. One panelist stated "I do not think that this is a critical distinction that needs to be drawn extensively for students, or greatly emphasized." Another noted that at the K-12 level it is better for students to see engineering and science as being connected rather than to see them as two different specializations. Regardless of some of the negative comments for this item, it did have support from a large number of participants and meets the criteria for inclusion in the final list.

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. Aspects such as *Design-Driven*, *Problem-oriented* and *Ethical* may have not achieved consensus and stability due to comments made by participants in Round 2 (see details above). Other aspects may have had less support from the beginning. For example, the aspect *Holistic* only had five comments, which is far fewer than other aspects. Other aspects, such as *Multidisciplinary* and *Contextual* showed consensus (greater than 75% rating as important or very important), but were below the line for stability (15% change in distribution between Rounds 2 and 3). While it is possible that some of these aspects 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.

Group Differences

In order to understand differences between group ratings, the results of the final list of aspects were analyzed by type of participant category (Engineering teacher, science teacher, engineering education faculty, and science education faculty). Because the participants were purposively sampled from experts in the field and were not intended to be a representative sample of their group, inferential statistics were not performed. Although some Delphi studies do include between group comparisons such as ANOVA (Osborne, 2003) 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 the mean would be useful in understanding group responses (see Table 9).

It is clear from Table 9 that most groups had similar ratings on the average. All groups had average ratings within 0.08 points of the overall mean of 4.48. Looking at individual aspects, most group ratings were within 0.15 points (one standard deviation) of the mean for that aspect. Some groups, however, had ratings that were greater than the standard deviation. Science education faculty rated *Criterion and Constraints* higher (0.20) than the aspect average and rated two aspects lower: *Creative (-0.22)* and a *Communicative (-0.23*). Engineering education faculty rated *Model-driven* and *A Unique Way of Knowing* lower than the aspect average (-0.35 and -0.43 respectively). Engineering teachers rated the *Communicative* aspect 0.18 points higher than the mean and *Constrained by Criteria* 0.27 points below the mean. Science teachers rated the *Creative* aspect 0.20 points higher than the average for that aspect. The *Design-Driven* aspect (removed due to lake of stability in Round 3) showed varied results across groups. The engineering-oriented groups both rated this aspect higher than average (0.27 for engineering teachers and 0.32 for engineering education faculty). The science-oriented groups both rated the *Design-Driven* aspect lower than the average (0.50 lower for K-12 teachers and 0.08 lower for science education faculty). Based on the comments from the science-oriented groups, 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 groups rated this aspect lower than the engineering-oriented groups. It is interesting to note that if the science-oriented groups were eliminated from the analysis, the *Design-Driven* aspect would have met the criteria for stability (8% of participants changing their rating between Rounds 2 and 3 which is well below the 15% stability cutoff). When completing the analysis on the engineering-oriented groups only, the rating for this aspect would have been 4.72 (on a five-point scale) which is higher than that the mean of the highest item (4.70) in the

Round 3 survey. Despite the high rating and stability of the engineering-oriented group, the ratings of the science-oriented groups caused instability between rounds that resulted in moving this aspect off the list due to low stability. Evaluating the groups in this manner gives some understanding to the mean ratings seen in Table 9. While the consensus of the entire group was the goal of this investigation, it is valuable to see group perspectives on individual items.

Final Survey

A final questionnaire was employed to gather additional information that is not included in the traditional Delphi methodology. This questionnaire gave participants the opportunity to define the term ‘Nature of engineering’ as well as giving feedback on the appropriate grade-level that the nature of engineering aspects should be introduced to K-12 students. The final questionnaire also provided participants the opportunity to comment on the final wording of the nature of engineering aspects. This process was valuable because it allowed the author to gather information from participants who experienced each of the three rounds of the Delphi. After participating in the discussions on the importance and priority of nature of engineering aspects, the participants were in a unique position to provide feedback on the meaning of the nature of engineering and when these concepts might best be introduced to students.

Defining the Nature of Engineering

Participants defined the nature of engineering by responding to a single prompt. Results from the qualitative coding process discussed above included six major components to the definition of the nature of engineering. These components were: The definition of engineering, its inputs, process, outputs, and ultimate goals. In defining the nature of engineering, almost all panel members described it using works like “design” or “problem-solving.” Words like “systematic” and “analysis” also appeared in a number of the definitions. A summary definition for engineering that would fit a majority of the responses is “Engineering is a profession that uses design under constraints to solve problems.”

The third component of the nature of engineering was the inputs to the engineering process. Participants saw mathematics and science as being core knowledge to the nature of engineering. In addition, the panel members viewed engineering as applying the knowledge from many disciplines, including economic, technology, practical, and social fields. However, science was the most reported field, followed by mathematics. Constrained by Criteria was another area of knowledge that participants viewed as important to the nature of engineering. While this type of input might not fit into an academic category as mathematics and science do, participants viewed it as important as well. Constrained by Criteria represents the limitations placed on engineering designs. These limitations may come from areas such as stakeholder needs, physical constraints, or costs required to make a product profitable. Participants saw these areas of input as critical to the engineering process.

The engineering process was identified as the fourth component of the nature of engineering. The engineering design process was described as an “iterative” and “systematic” process of design. Instead of pursuing this process alone, participants noted that engineers often work “collaboratively” with team members from many different backgrounds. The design process includes many steps and may include analysis, design, building, testing and optimizing. Ultimately, the design process is not a monolithic template that can be applied to all engineering situations. Participants noted that the process needs to be flexible and “…take into consideration cultural and individual perspectives.” This component of the nature of engineering is the where action is performed in engineering.

The fifth component of the nature of engineering was identified as the outputs of the design process. Participants identified both products and processes as key outputs of the engineering design process. Regardless of the type, many recognized the output of the engineering process as simply a set of ideas. While engineers may be involved in the construction of a physical product, their primary focus is the “best solution” or “optimized process.” While some participants mentioned “tangible products” many recognized that engineers may be designing non-tangible items such as processes or systems. In general, participants recognized engineers were responsible for creating products or processes that solved a real-life problem.

The sixth and final component to the nature of engineering was identified as the overarching goal of engineering. Most respondents included aspects of developing solutions that meet needs or wants. Some participants identified the solution as “technological” in nature and resulting in an improvement of the “human-made world.” The solution of these problems was recognized by many as having a “benefit to society” and “improving the human condition.” Some panel members noted the problem did not need to be only local in scope. Engineering can solve problems that impact people on a regional, national, and global scale as well. This goal of engineering as described by participants was to meet the needs of humans by developing solutions to problems.

A general answer to the meaning of the nature of engineering can be constructed by combining the components identified by the participants. Panel members described the nature of engineering as how engineers think and work. The nature of engineering can be further defined through the use of a definition, inputs, process, outputs and overarching goal. Thus, a succinct definition of the nature of engineering is, “An iterative process that uses mathematics, science, criteria, and constraints to design solutions to human needs or wants.”

Grade-level Implementation Recommendations

Participants identified the optimum grade-level to introduce each of the nature of engineering aspects on the follow up survey (see Table 10). On the average, participants viewed the nature of engineering as a topic that could be introduced between grades K-2 and grades 3-5 (1.92 on a scale of 1=’K-2’, 2=’3-5’ 3=’6-8’, 4=’9-12’). The recommended grade-level to introduce these aspects was relatively narrow with a range from 1.38 to 2.37. This means that all nature of engineering aspects would be introduced to students beginning approximately in grade one and ending approximately in grade four. Panel members recommended introducing *Creative* (1.38) and *Constrained by Criteria* (1.62) earliest to students. They further recommended aspects of the nature of engineering such as *Iterative* (2.37), *Communicative* (2.33); *Collaborative* (2.31) be introduced to students when they are older.

Some participant groups recommended students be taught nature of engineering aspects at an earlier grade than the average. Both science teachers and engineering education faculty recommended these aspects be introduced somewhat earlier (4% and 5% below the average respectively). Science teachers recommended aspects such as *Creative* and *Iterative* be taught approximately one year earlier than the rest of the participants (0.21 and 0.19 points lower than the mean respectively). Science education faculty recommended the concept *Iterative* and *A Unique Way of Knowing* be taught approximately one grade-level earlier (0.27 and 0.25 points lower than the mean respectively). Engineering-oriented participants, on the average recommended that students learn about nature of engineering aspects somewhat later than the average (0.8 and 0.9 points greater). Specifically, engineering teachers recommended that students learn about aspects such as *Iterative*, *Collaborative*, and *Communicative* approximately one year later than the other participant groups (0.23, 0.23, and 0.21 points greater than the mean). Engineering education faculty recommended aspects such as *Iterative* and *A Unique Way of Knowing* be introduced later (0.36, 0.31 and 0.31 points greater than the mean respectively). Despite these specific differences, participants generally recommended that students should first learn about nature of engineering expects early in elementary school (between Kindergarten and grade five). No participant group recommended introducing nature of engineering aspects any later than third grade (corresponding to a rating of greater than 2.33). This indicates that nature of engineering aspects are simple enough for younger students to understand.

Table 8

Aspects and Ratings from Rounds 2 and 3

	Round 2				Round 3			
Aspect and Summary Statement	Mean	Mode	SD	%>4	Mean	SD	%>4	Stability
Divergent The solution to an engineering problem is but one attempt to meet criteria while staying within constraints. There is rarely one right answer to engineering problems. Multiple successful solutions are possible.	4.52	5	0.74	89%	4.70	0.46	100%	9%
Creative Engineers use creativity in addition to logical thinking throughout problem identification, design, implementation, and communication processes.	4.40	5	0.75	90%	4.52	0.68	93%	8%
Iterative Learning from failure is important to engineers because early designs often do not meet criteria and constraints. They analyze these early failures to identify issues and improve the design so the final solution can be successful.	4.38	5	0.81	83%	4.52	0.70	92%	8%
Model-driven Engineers develop models (e.g. mathematical, visual, or physical) to support design, testing and implementation to reduce the risks of building full-scale items.	4.37	5	0.79	84%	4.52	0.62	97%	12%

(Continued)

Holistic Engineers often requires a way of thinking that emphasizes the ability to understand how the parts of a system work together (systems thinking).	4.37	5	0.77	83%	4.50	0.54	98%	19%
Communicative Engineering requires communication between team members and other stakeholders.	4.46	5	0.71	90%	4.47	0.62	93%	8%
Constrained by Criteria Engineering designs must meet constraints (such as economic, environmental, social, safety, etc.) and are evaluated against criteria (such as economic feasibility, performance, risk of failure, public interests, etc.).	4.52	5	0.67	94%	4.45	0.70	95%	11%
Design-Driven Engineers follow a semi-structured process to develop technical solutions that may involve iterative cycles of design, testing, and improvement. The steps of the process may vary by discipline and situation.	4.54	5	0.78	89%	4.43	0.74	93%	23%
Multidisciplinary Engineers use science, mathematics, technology and other disciplines to develop solutions to problems.	3.79	5	1.02	65%	4.42	0.77	92%	16%
Collaborative Engineering work is typically a team effort with input and knowledge spread among many people with varied expertise.	4.52	5	0.64	95%	4.40	0.72	87%	13%

(Continued)

Ethical Engineers have ethical responsibilities. While engineering often follows the ethics of utility (greatest benefits given the costs), engineers also have a duty to consider the negative consequences of designs such as impacts to minority groups and the environment	4.38	5	0.77	83%	4.30	0.74	87%	17%
A Unique Way of Knowing Engineers expand engineering knowledge through empirical tests, experience, and applying science and mathematics. These processes are related to but distinct from the way science expands knowledge. Science begins with questions about phenomena in the natural world, whereas engineering begins with defining a problem in need of a solution.	4.02	5	1.01	75%	4.27	0.76	85%	10%
Contextual Engineering solutions are dependent on the issues and situations for which they are developed. Engineering is influenced by the context of the solution so understanding the user is important to the Design-Driven. Culture and language are part of the context along with government, geography, and economic systems.	4.05	4	0.87	76%	4.25	0.57	93%	19%
Product and Process-Oriented Engineers develop products, and other types of outputs such as processes, and protocols.	3.92	5	1.07	68%	3.87	0.72	73%	34%
Problem-oriented 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.	4.62	5	0.58	95%	3.80	1.07	67%	31%

(Continued)

Inclusive of Multiple Disciplines Engineering is not one fixed entity. There are many types of engineering (e.g. biological, chemical, civil, electrical, mechanical, etc.), each with their own unique approach to the field.	3.79	4	1.02	65%	---	---	---	---
Accessible Engineering knowledge has been created by many cultures, making it diverse and accessible to everyone	3.79	4	1.08	63%	---	---	---	---
Historical Engineers understand not only the current ways to solve a problem, but also the historical development of engineering and the technologies it creates.	3.32	3	1.04	38%	---	---	---	---

Note. Items rated from 1=not important to 5=very important

Table 9

Importance of Nature of Engineering Aspects for Delphi Round 3 by Group (n=60)

	K-12				University				
Aspect	Engineering teachers		Science teachers		Engineering Faculty		Science Faculty		Mean
n	17		14		12		17		--
A Unique Way of Knowing	4.41	(0.15)	4.36	(0.09)	3.83	(-0.43)	4.35	(0.09)	4.27
Collaborative	4.53	(0.13)	4.43	(0.03)	4.33	(-0.07)	4.29	(-0.11)	4.40
Constrained by Criteria	4.18	(-0.27)	4.43	(-0.02)	4.58	(0.13)	4.65	(0.20)	4.45
Communicative	4.65	(0.18)	4.43	(-0.04)	4.58	(0.12)	4.24	(-0.23)	4.47
Model-driven	4.65	(0.13)	4.50	(-0.02)	4.17	(-0.35)	4.65	(0.13)	4.52
Iterative	4.47	(-0.05)	4.50	(-0.02)	4.50	(-0.02)	4.59	(0.07)	4.52
Creative	4.59	(0.07)	4.71	(0.20)	4.50	(-0.02)	4.29	(-0.22)	4.52
Divergent	4.59	(-0.11)	4.71	(0.01)	4.67	(-0.03)	4.82	(0.12)	4.70
Mean	4.51	(0.03)	4.51	(0.03)	4.40	(-0.08)	4.49	(0.01)	4.48

Note. Numbers in parenthesis are differences from the mean for the aspect.
Aspects were rated on the scale 1=not important to 5=very important.

Table 10

Optimum Grade-level to Introduce Nature of Engineering Concepts by Group (n=52)

	K-12				University				
Aspect	Engineering teachers		Science teachers		Engineering faculty		Science faculty		Mean
n	12		12		12		16		--
Creative	1.50	(0.12)	1.17	(-0.20)	1.33	(-0.05)	1.50	(0.12)	1.38
Collaborative	1.83	(0.21)	1.50	(-0.12)	1.50	(-0.12)	1.63	(0.00)	1.62
Iterative	2.00	(0.23)	1.58	(-0.19)	2.08	(0.31)	1.50	(-0.27)	1.77
Communicative	2.00	(0.23)	1.67	(-0.10)	1.83	(0.06)	1.63	(-0.15)	1.77
Divergent	2.00	(0.19)	1.75	(-0.06)	1.67	(-0.14)	1.81	(0.00)	1.81
Unique Way of Knowing	2.25	(-0.06)	2.33	(0.02)	2.67	(0.36)	2.06	(-0.25)	2.31
Constrained by Criteria	2.25	(-0.08)	2.25	(-0.08)	2.50	(0.17)	2.31	(-0.02)	2.33
Model-driven	2.17	(-0.20)	2.50	(0.13)	2.67	(0.30)	2.19	(-0.18)	2.37
Mean	2.00	(0.08)	1.84	(-0.08)	2.03	(0.11)	1.83	(-0.09)	1.92

Note: Numbers in parenthesis are differences from the mean for the aspect.
Grade levels were rated on the scale 1=’K-2’, 2=’3-5’, 3=’6-8’, 4=’9-12’.

CHAPTER 5 -- DISCUSSION

Summary of Prior Research

Interest in engineering for K-12 education has grown significantly in recent years. Many states have begun to include engineering as part of their science education standards. Similarly, national organizations have included engineering as a core component of pre-college education. The NGSS has listed engineering practices and core ideas as a critical part of K-12 education. In addition, the ITEEA technology standards have identified an understanding engineering as being part of technology education. These efforts have not, however, emphasized the nature of engineering and how engineering knowledge is developed. Despite the increased emphasis on engineering in K-12 education, there is little research to guide the development of curriculum that includes the three main components of engineering literacy: Engineering body of knowledge, engineering practices, and the nature of engineering (ASEE, 2014b).

Efforts to date to include engineering in K-12 education have emphasized either the engineering body of knowledge or engineering practices and have not focused on the nature of engineering. For example, the NGSS includes engineering practices that are integrated with science practices as a key component of science education (NGSS Lead States, 2013). The NGSS also includes a short section that describes disciplinary content knowledge of engineering design. The ITEEA technology standards, however, only discuss engineering design briefly in the introductory material and do not include engineering aspects in the standards themselves (ITEEA, 2007). Research has been conducted on the engineering body of knowledge K-12 students should know before they graduate from high school (Childress & Rhodes, 2006; Childress & Sanders, 2007). These efforts can guide the development of curriculum for technology, mathematics, and science classes but do not help students what the nature of engineering is.

Additional research has been conducted in understanding teacher views of engineering as a field. Teachers have been surveyed to understand what conceptions they have of engineering (Cunningham et al., 2005; Lambert et al. 2007). These studies show that many teachers have a limited view of the engineering profession and some hold misconceptions of the field. This line of research highlights that lack of engineering understanding by teachers but does not put forward conceptions that would be appropriate for K-12 students and teachers understand about engineering. 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. 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. The purpose of this dissertation was to empirically develop aspects of the nature of engineering that would be appropriate for K-12 students to learn.

Comparisons to the NGSS

Although the NGSS does not include nature of engineering aspects as part of the standards for students to learn, the National Academies and Lead States do describe compatible concepts at various locations in the introductory book the Framework for Science Education (NRC, 2011). In the NGSS Framework, the descriptions of aspects of the nature of engineering are not presented as the results of empirical investigations. Instead, they are brought up in various contexts throughout the document. Instead of being presented in a table as aspects of the nature of engineering, they can only be located by searching the text for aspects identified in the present investigation. The results of this search yielded six brief discussions of engineering that are somewhat similar to the aspects developed through the Delphi process (NRC, 2011). It is important to note that the term "Nature of engineering" is not used in the NGSS framework. The references identified in the NGSS document are therefore inferences to the concepts being aspects of the nature of engineering. Table 11 shows how the NGSS treatment of the nature of engineering compares to the results of the current investigation. Of the eight nature of engineering aspects identified by experts in the present research, six were located in the NGSS Framework text.

In evaluating the first nature of engineering aspect, the NGSS identifies engineering as developing multiple solutions to the problem that is being solved. The authors of the NGSS state that "The optimization process typically involves tradeoffs between competing goals, with the consequences that there is never just one 'correct' answer to a design challenge" (NRC, 2011, p. 41). This statement aligns with the

Divergent aspect. Experts noted that there is rarely one right answer to engineering problems and that multiple successful solutions are possible.

The second nature of engineering aspect *Creative* is also discussed by the NGSS Framework. The NGSS describes the creative process that is required to develop a solution to an engineering problem as "…a central element of engineering" (NRC, 2011, p. 206). The authors of the NGSS Framework describe the engineering process as beginning with an open-ended phase in which creativity is required to develop solutions that may be developed and tested further. This approach lines up with the expert views identified in the present investigation of creativity as an important part of the problem identifying the problem, designing the solution, and testing solutions.

The third aspect of the nature of engineering, *Iterative,* is discussed in the NGSS Framework as the process of iteration. The NGSS Framework describes failure as a part of the iterative process that helps engineering find a solution that best meets the specifications. For example, the authors note that "Tests are often designed to identify failure points which suggest elements of the design that need to be improved" (NRC, 2011, p. 207). This process repeatedly develops and tests models that are iteratively improved as failure points are identified. This approach is very similar to the nature of engineering aspect identified by experts in the current investigation. They described engineers as learning from failure. Engineering often expect their initial designs to have flaws. After testing, these flaws become evident and the engineering learns what does not work. Future designs can be modified so that a successful final solution can be found.

Model-driven, the fourth nature of engineering aspect, is also described by the NGSS Framework. One of the scientific and engineering practices identified in the NGSS standards themselves is ‘Developing and Using Models’. The NGSS Framework identifies models as a critical part of the engineering process. They state that “Models allow the designer to better understand the features of a design problem, visualize elements of a possible solution, predict a design’s performance, and guide the development of feasible solutions” (NRC, 2011, p. 206). They note that models can be physical, graphical, and mathematical. This view of modelling is similar to the nature of engineering aspect identified by the experts in the present investigation. They described modelling as a way to support design, testing, and implementation specifically to reduce the risks associated with building a full-scale solution.

The fifth nature of engineering aspect, *Communicative*, is discussed in the NGSS Framework as the need to communicate results. The NGSS includes ‘Obtaining, Evaluating, and Communicating Information’ as a key science and engineering practice. Specifically, the NGSS Framework makes that case engineers are unable to develop new technologies unless they are “..communicated clearly and effectively” (NRC, 2011, p. 278). By identifying communication as one of the key practices of engineering, the NGSS Framework emphasizes this aspect of the nature of engineering as being important.

Constrained by Criteria was the sixth aspect identified by experts as important in K-12 education. This aspect has a number of references in the NGSS Framework. For example, the Framework describes criteria and constraints as one of the key elements that are different between science and engineering. The NGSS Framework authors note that “These elements include specifying constraints and criteria for desired qualities of a solution…” (NRC, 2011, p. 68). This approach is similar to the concept identified by the experts in the present Delphi study. They described engineering designs as being evaluated with multiple types of criteria and constraints.

The seventh aspect, *Collaborative*, was not clearly identified as being a part of the nature of engineering. The NGSS Framework describes a step in the engineering process as requiring brainstorming sessions to develop potential solutions to problems. However, the majority of the NGSS Framework appears to represent engineering as an individual pursuit. This is in contrast to the experts in the present investigation. They described engineering as primarily a collaborative effort. In their view, engineers typically work as a member of a team that has many difference skills and expertise.

The final aspect of the nature of engineering identified by experts in the present investigation was engineering as *A Unique Way of Knowing*. This concept is not clearly delineated by the NGSS Framework. The NGSS Framework does describe the engineering process as being different than the science process. They identify areas in which engineering diverges from science in its approach. However, the NGSS Framework does not clearly identify the nature of engineering knowledge as being different than science. In many ways, the NGSS Framework presents engineering as an application of science instead of its own unique way for knowing. This makes sense in light of the NGSS Frameworks explanation for why engineering and technology were included in the NGSS: “As applications of science” (NRC, 2011, p. 11).

Despite not being developed through empirical research; some concepts can be located in the NGSS Framework even though the nature of engineering is not discussed explicitly in the text. It was possible to locate discussion of the aspects of the nature of engineering only by conducting keyword searches within the document. Because these concepts are not organized or presented as being part of the nature of engineering, policy makers, curriculum designers, and teachers would not be able to identify them for use in their curriculum efforts. Even though these aspects are not identified in the NGSS Framework text, a number of the concepts can be located and it can be said that a majority (75%) of the aspects developed in the present study are compatible with the NGSS Framework. Beyond being compatible, the Framework does not explicitly discuss any aspects of the nature of engineering as described in the present study.

Comparisons to American Society of Engineering Teacher Standards

The results from the present study can also be compared to the ASEE engineering teacher standards. The standards were developed to outline important concepts for K-12 engineering teachers to understand about the nature of engineering (ASEE, 2014b). Farmer and Nadelson, the authors of this report, developed a description of the “Nature, Content, and Practices of Engineering.” Six of the items outlined in this standards document match the aspect identified by the experts in the present investigation (see Table 11). Because the ASEE teaching standards outline each aspect with a short phrase describing each aspect, it is difficult to go into much detail regarding the meaning of each item.

The ASEE teaching standards (2014b) describe the process of using failure to learn from design experiments. This is a similar concept to the Iterative aspect named by the participants of the present study. The ASEE standards note that "When designed solutions fail, engineers learn from this failure and improve based on this new knowledge." This definition clearly outlines the *Iterative* process where previous designs are improved by evaluating the failure-points.

The ASEE engineering teacher standards also identify engineering as developing multiple solutions. The standards (ASEE, 2014b) describe engineering as assuming that each engineering problem can have multiple solutions. This wording is similar to the wording used by participants in the present study when describing the *Divergent* aspect of the nature of engineering. Participants emphasized that there is not one correct answer to an engineering problem. Instead, multiple solutions can equally balance the competing constraints. The ASEE (2014b) standards match the *Divergent* aspect of the nature of engineering as described by the participants of the present study.

The aspect *Creative* is also described in the ASEE engineering teacher standards. The document states that engineering "Is inherently innovative and creative." The experts in the present study also viewed engineering as creative. They recognized that much the current K-12 curriculum is not presented as encouraging creativity. They saw engineering as encouraging creativity and innovative thinking. The ASEE standards (2014b) describe the concept of creativity in a similar way to expert view of creativity as being an integral part of the engineering process.

Constrained by Criteria are included in the ASEE engineering standards as an important concept for engineering teachers to know and pass on to their students. The standards note that engineering "involves design under constraints." This portion of the standard describes engineering similarly to the experts in the present investigation. The experts described engineering designs as being evaluated against criteria and constraints that required optimizing the solution.

Finally, the ASEE engineering teacher standards recognize that engineering is *Collaborative and Communicative*. The authors of the standards describe someone who is engineering literate to understand that engineering "Is collaborative and team-oriented." They also describe engineering as using multiple means of communicating results. Both of these descriptions are in line with the experts in the present investigation who viewed engineering as an activity that requires a communication within team of experts, each with different skills.

Two nature of engineering aspects were not included in the ASEE engineering teacher standards: *Model-driven* and A *Unique Way of Knowing*. While the concept of modelling is not included under the nature of engineering heading. Additionally, the standards do not emphasize the uniqueness of the engineering way of knowing.

To summarize, thee ASEE engineering teacher standards include 75% of the aspects identified by experts in the present Delphi investigation, based a comparison of the brief statement provided by the authors. Most of the aspects described in the ASEE document are between four and six words in length. Because the document does not expand on each of the items in the list, it is difficult to know whether they are truly similar to the aspects of the nature of engineering identified by the experts in the present study. It is interesting to note that the ASEE teaching standards (2014b) were developed by a consensus-building process, the focus group. By bringing a group of engineering teachers together, the authors of the standards developed a list that is similar on the surface to the present study. However, the lack of a detailed description of each aspect requires that assumptions be made regarding the meaning of each concept. Only further elucidation of each aspect by the ASEE team would determine where the aspects are truly similar or not.

Comparison to Karatas Nature of Engineering Tenets

Although not empirically based, the Karatas (2009) description of nature of engineering tenets represents the most complete work in the literature to date. The tenets were developed for use in post-secondary settings but concepts could easily be applied to K-12 situations. The tenets were based on a summary of the literature and represent a comprehensive view of the nature of engineering from this standpoint. The following paragraphs describe Karatas (2009) descriptions of the tenets of the nature of engineering in comparison to those developed in the present investigation.

The first aspect of the nature of engineering, *Divergent*, is not included by Karatas (2009) in his list of tenets of the nature of engineering. Karatas (2009) describes engineering solutions as being tentative because they are a solution for a particular time. Improvement can be made on this design, leading to another solution that meets the needs at that particular time. This tenet as described by Karatas (2009) is not the same as the *Divergent* aspect identified by participants in the present study. The *Divergent* aspect of the nature of engineering describes a situation where two solutions to an engineering problem meet the needs of the stakeholders in different ways, but are still considered successful solutions. Participants noted that there rarely "right" answers to an engineering problem. There are multiple divergent solutions to that can achieve the goals of the project while balancing constraints. Karatas (2009) does not describe this aspect of the nature of engineering in his review of the literature.

Karatas (2009) describes engineering as being a *Creative* endeavor similarly to the experts in the present investigation. He describes "Creativity as being needed for every step of the engineering process…" (p. 39). Creativity is desire to solve a problem that many believe is impossible. The experts in the present investigation noted that creativity is required for every step of the engineering design process. While some may believe that creativity is only required during the brainstorming phase of the project where multiple solutions to the problem are evaluated, both Karatas (2009) and the participants in the present study disagree. Karatas (2009) describes the entire design process as being infused with creativity. This view is echoed in the present study. Creativity is required in problem identification, brainstorming solutions, design, testing, and communicating the final results. Both the present study and Karatas (2009) identify the *Creative* aspect of the nature of engineering.

The third aspect of the nature of engineering identified by experts was *Iterative*. The experts saw failure as an inevitable part of the design process. A potential design doesn't always work as intended and the engineer must determine what failed and improve the design. Similarly, Karatas (2009) identifies failure as an important tenet of the nature of engineering. He describes large-scale failures engineers must learn from and ensure will never happen again. Without the concept of learning from failure, engineers would repeat the failures of the past and never improve their designs. This cycle of *Iterative* improvement of a design is described by Karatas (2009) as the "Tentative and temporary" nature of engineering products. A design is never fully finished. A design balances the constraints of the project and meets the needs of the present time as best as possible. This does not mean that in the future the design will be changed and improved to meet the needs in different ways. The participants in the present study describe the Iterative aspect of the nature of engineering in similar ways to the summary of the literature presented by Karatas (2009).

Karatas (2009) describes the aspect *Constrained by Criteria* as the process of "Decision Making." In this tenet, Karatas (2009) points out that engineering requires many decisions in order to optimize the best way to meet the requirements of the project. Choosing to emphasize one characteristic of the engineering product (e.g. price) is likely to influence other characteristics of the product (e.g. performance or quality). Karatas (2009) focuses on the decision making process that is required to develop the best solution given the constraints. Experts in the present investigation also viewed engineering design as developing a solution that meets the criteria in the best possible way, although they did not emphasize the decision-making process. These criterial provide constraints that limit the design in potential conflicting ways. The participants in the present study pointed out that engineers may increase the performance of a product only decrease the environmental compatibility of the design. Rather than developing one solution to a problem, the solution is an optimization of the largest number of requirements, and constraints possible. The notion of being *Constrained by Criteria* was present in both the present work and that of Karatas (2009), although they approached the aspect in different ways.

Finally, Karatas (2009) describes a tenet called “Social and Cultural” that might appear to be related to the *Collaborative* nature of engineering outlined in the present study. The participants in the present study emphasized that engineering is a team effort that involves a diverse group of people that each bring different types of expertise to the problem. One example, the team designing a car might include electrical engineers, mechanical engineers, industrial designers, materials specialists, testers, and project leaders, to name a few roles. This entire team must work collaboratively in order to complete the design. Panel members in the present study noted that most (but not all) engineer works requires this type of team effort. Karatas

(2009) does not emphasize this aspect of engineering. The “Social and Cultural’ tenets focuses on engineering as a social institution. He describes engineering as developing technology that is a product of the values and culture in which it is embedded. Karatas (2009) further portrays engineering as being a social activity that meets social needs. While this concept could be expanded to emphasize the *Collaborative* nature of engineering, Karatas (2009) does not. So, while his “Social and Cultural” tenet of engineer appears on the surface to be similar to the *Collaborative* aspect identified by participants in the present study, they are two different concepts.

Karatas (2009) provides the most detailed and organized list of tenets of the nature of engineering available in the literature. He includes three of the eight (38%) aspects developed by the experts in the present investigation. Although a small number of aspects overlap with those developed in the present investigation, they are organized and described in detail with citations in contrast to the NGSS Framework and the brief titles given by the ASEE engineering teacher standards. Karatas (2009) does not include aspects such as *Divergent*, *Model-driven*, *Communicative*, *Collaborative*, or *A Unique Way of Knowing*. While Karatas (2009) defined a small number of tenets that are similar to the aspects of the nature of engineering in the present study, he did not describe the majority of aspects that the experts believed were important.

It is interesting to evaluate the aspects that were included by all three comparison efforts (ASEE, 2014b; Karatas, 2009; NRC, 2011) but not identified as being important to the participants of the Delphi study. All of these publications included 'Design' as a key component of the nature of engineering. As discuss in the results section, *Design-Driven* was the highest rated aspect by engineering-oriented participants, but instability from science-oriented participants pushed it out of the final list. Based on comments, the science-oriented participants were concerned that the engineering design process might become a series of steps that would be memorized by K-12 students. It is interesting to speculate on whether the word 'Design' without the word 'Process" would have had such a strong connotation. In addition, the "Holistic" concept was included by all of the comparison literature. This concept was included in Round 1 and Round 2, but was removed due to poor stability in Round 3.

Summary

While there are potentially a large number of individual aspects that could be considered appropriate for K-12 education, the goal of this research was to find aspects that could be agreed upon by stakeholders in the field: K-12 teachers and university faculty. Indeed, a total of 19 aspects were suggested during Round 1 for potential inclusion in the list. While it is not likely that a consensus would be developed on this larger set of aspects, agreement on a small subset of aspects 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 aspects. While additional aspects 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 be launched to expand and validate these findings.

It is clear that teachers would benefit from understanding the nature of engineering in a more complete way. As noted earlier, the teachers that have been studied to date have a limited view of engineering. In addition, the research has pointed out various misconceptions of engineering that are held by some K-12 teachers. Research such as the present investigation can provide a more complete understanding of the nature of engineering for the development of classroom curriculum and teacher in-service programs.

A concern in identifying a collection of items important to the nature of engineering in K-12 education is that these aspects may be taught as an isolated list separated from their meaning. Other researchers have identified this potential issue in science education (Wong & Hodson, 2009; Osborne, 2003) 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 aspects identified in this investigation are not intended to serve as a definitive list of aspects of the nature of engineering. A number of participants commented on the inter-relatedness of aspects and the potential for adding additional aspects. Michael Matthews (2011) argued 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 participants responding to the study invitation, 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 aspect 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 clarify the aspects that were developed. The results of the present work are intended to provide support for curriculum development and policy creation. While the list of nature of engineering aspects may be useful for guiding classroom instruction, current empirical research from the nature of science literature supports teaching the concepts explicitly in the context of relevant engineering content (Eastwood, et. al 2012; Matkins & Bell, 2007). Utilizing this approach in nature of engineering instruction will encourage teachers emphasize the conceptual nature of the aspects and may reduce the tendency to teach them as a decontextualized list of terms to be learned.

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 an aspect as important or very important. In addition, stability was defined as less than a 15% change in distribution between Rounds 2 and 3. A number of items met the consensus requirement, but not the stability requirement by Round 3. These items include *Holistic* (4.50 rating on a 5-point scale), *Design-Driven* (4.43 rating), *Multidisciplinary* (4.42 rating), *Ethical* (4.30 rating), and *Contextual* (4.25 rating). It is important to note that the aspect *Design-Driven* is often listed as a key component of engineering (See Table 11). In the present investigation, *Design-Driven* was highly rated in Rounds 2 and 3, but did not achieve stability in Round 3. As noted earlier, this was likely because science-oriented participants were concerned that including *Design-Driven* in the aspects of the nature of engineering could become a codified process list similar to the “Scientific Process”. The engineering-oriented groups did not mention this issue, and the aspect showed stability between Round 2 and Round 3 for this group. If the word “Process” had been removed from the title, it is possible that this aspect would achieved the necessary stability to the entire group (including science and engineering groups) to be included in the final list. With additional rounds or a different group of participants, these concepts might have been included in the final list of aspects. 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.

The goal of this study was to understand aspects of the nature of engineering that would be at the appropriate level for K-12 students. Sixty-five panelists with backgrounds as engineering teachers, science teachers, engineering education faculty, and science education faculty began Round 1 of Delphi process. Sixty panelists (92%) completed all three rounds of the Delphi methodology. These experts in engineering education identified eight aspects that they believed were important helping K-12 students understand the nature of engineering. These aspects showed both consensus and stability throughout the Delphi process. This work is an important step in understanding the nature of engineering and how it can be taught to K-12 students. These empirical results can provide foundation for future policy development at the state and national levels. In addition, these nature of engineering concepts can be used to develop curriculum and classroom materials that expose students to a broader view of engineering. With the increasing interest in K-12 engineering in science education, future students will not only be able learn about engineering practices and the body of engineering knowledge, but they will also be able to gain a better understanding of the nature of engineering. With this background they will be much more engineering literate and able to understand how engineering is a part of our world.

Table 11

Comparison of Approaches to the Nature of Engineering

This Investigation	Karatas (2009)	ASEE (2014a)	NRC (2011)
Divergent	Tentative / temporary	Multiple solutions	Many solutions, tradeoffs
Creative	Creativity, imagination, and integration	Creative	Requires creativity
Iterative	Theory, artifact, and failure Laden	Failure as learning	Iterative
Model-driven			Models
Communicative		Requires many ways of communicating	Reasoning from evidence
Constrained by Criteria	Decision making	Constraints	Develops constraints and criteria
Collaborative	Social and cultural	Collaborative	
A Unique Way of Knowing			
	‘The’ design process	Design	Technical design
			Stakeholder needs
		Problem solving	
		Theory and practice	
	Holistic	Systems thinking	Systems thinking

CHAPTER 6 – DISCUSSION AND CONCLUSION

The purpose of the present study was to better understand aspects of the nature of engineering that are important for K-12 students to learn. The end goal of the study was to provide a framework of the nature of engineering that could be used for policy, research and curriculum development. The experts that participated in the study represented four important groups that are involved in K-12 engineering education: K-12 engineering teachers, K-12 science teachers, engineering education faculty, and science education faculty. The Delphi process identified eight aspects of the nature of engineering that participants viewed as important for K-12 students to learn. The highest rated aspects were *Divergent*, *Creative*, and *Iterative*. These results provide a foundation for improving engineering at the K-12 level.

Recommended List of Aspects for Future Use

One of the aspects of the nature of engineering that is not included in the final list is that of *Design-driven*. The *Design-driven* aspect (named the Design Process at the time) was included in the themes developed from the open-ended Round 1 survey and in the quantitative Round 2 rating survey. In fact, *Design-driven* was the second highest rated aspect on the Round 2 survey. However, in the Round 3 survey, 23% of the respondents changed their rating of the aspect, indicating low stability of this item. An analysis of the qualitative comments provided by participants, indicated that science teachers, in particular, had concerns that the engineering process would be taught as a list of steps in the K-12 classroom. They commented that they did not want this to occur in a similar way to that of the science process, which is described as a six-step process in some classrooms. Furthermore, the engineering teachers and faculty did not show this high level of instability on this item.

Because engineering design is considered foundational to the field, it is recommended that is be included in future lists of aspects of the nature of engineering. All the treatments of the nature of engineering for K-12 or university education discussed in the present study (ASEE, 2014b; Karatas, 2009; NRC, 2011) include design as one of the key aspects of the nature of engineering. The engineering-oriented groups of participants in the study rated this item (*Design-driven,* 4.72) higher than the top-rated item in the survey, *Divergent* (4.70). Only the K-12 science educators rated the item .50 points lower (on a five-point scale) than the average for all groups. For these reasons, it recommended to include the Design-driven aspect on the final list of aspects of the nature of engineering.

Three aspects developed in the present study are recommended to be treated as practices of engineering instead of aspects of the nature of engineering. The aspects of *Creative*, *Communicative* and *Collaborative* are listed as practices or skills that are common to many fields. As an example, a consortium of K-12 schools, universities, and businesses, defines Creativity, Communication, and Collaboration as key skills for all jobs in the 21st Century (Partnership for 21st Century Learning, 2016). In addition, the NGSS (2013) describes *Communication* as one of the practices of science and engineering. The NGSS (2013) also discusses the use of creativity and collaboration in defining problems and developing solutions (engineering practices). These practices are not unique to engineering as noted by a number of participants of the present study. It is recommended that these practices of engineering be described as important, but not unique to engineering. What it is not recommended to include them in the list of aspects of the nature of engineering, there is value in describing their importance in engineering design.

Finally, it is recommended to discuss the *Unique Way of Knowing* aspect separate from the other aspects. This aspect relates to the way in which engineering acquires knowledge. While the participants believed it was important to the nature of engineering, this concept would be better discussed as it relates to the whole of engineering as a field. It is important for student to understand the engineering is different than science. A number of participants underscored this perspective. However, this is an overarching concept in engineering and not an aspect of the nature of engineering that belongs with the other items.

After taking these recommendations, the list of aspects of the nature of engineering to be included in K-12 education drops from eight to five. The six aspects of the nature of engineering include: *Design-driven*, *Divergent*, *Iterative*, *Model-driven*, *Constrained by Criteria*. These aspects are sometimes thought of as being unique to engineering and other design-oriented disciplines. Four additional aspects could be included in the list as achieving consensus, but at a lower level of stability (less than 20% of participants changing their responses between Round 2 and Round 3): *Holistic*, *Multidisciplinary*, *Ethical*, and *Contextual*.

Implications for Teaching and Curriculum

With the inclusion of engineering in the NGSS, a 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 students to graduate from high school with an exposure to engineering but with an incomplete view of the nature of engineering. 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.

Integrating the aspects of the nature of engineering developed in the present investigation into existing frameworks will require significant effort. While many of these aspects are included in various locations in the NGSS Framework, they are not presented as ideas that student should learn. Only two of the aspects developed in this investigation are included in the NGSS standards documents themselves. The two aspects that are included in science and engineering practices are: *Model-driven* (practice 2, developing and using models) and *Communication* (practice 8, obtaining, evaluating, and communicating information). While these aspects are important to the nature of engineering, they are also shared by science. Instead of discussing the nature of engineering similarly to its coverage of the nature of science, the NGSS standards emphasize the engineering design process – something that was de-emphasized by the science experts participating on the Delphi panel. The lack of unique nature of engineering concepts in the NGSS itself (such as *Divergent* or *Constrained by Criteria*) mean that significant effort will be required to integrate these concepts in to existing K-12 curriculum.

It is important to note that the even though the NGSS standards themselves only cover a small percentage of the aspects of the nature of engineering developed in the present investigation, additional aspects can be found in the NGSS Framework with diligent effort (NGSS Lead States, 2013). The in the course of discussing the background for the NGSS, the Framework authors touch on aspects of the nature of engineering in various locations throughout the document. These aspects are not identified as being related to the nature of engineering and they are not organized and titled as the nature of engineering concepts. However, six of the aspects of the nature of engineering can be located by thoroughly searching the NGSS Framework using the aspects of the nature of engineering identified by the Delphi process. For example, the nature of engineering aspect *Creative* is discussed in the NGSS Framework under the title “Developing Possible Solutions”. This section describes a part of the disciplinary content knowledge (DCI) that students are to learn about engineering. Although the text describes creativity as being important to the problem solving process, it does not identify this concept as being and aspect of the nature of engineering. This aspect could only be located in the NGSS Framework by searching for the term “Creative” in the document. The NGSS Framework does not identify or highlight aspects of the nature of engineering. However, a majority of the aspects identified in the present study can be located in the text. The aspects of the nature of engineering aren’t entirely new to the NGSS, but they must be pointed out and developed. Rather than developing a set of nature of engineering curriculum based on completely new concepts, teachers will be able to build upon work that has started in the NGSS Framework.

The effort of improving teacher understanding of the nature of engineering will naturally be at the foundation of any efforts to improve the understanding of K-12 students. It is clear from the existing research that teachers have a relatively narrow understanding of the field of engineering (Cunningham et al., 2006; Lambert et al. 2007). The ASEE standards for engineering education teachers provide a solid foundation from which professional education programs could be developed. Although the standards lack sufficient detail to be used to understand each component of the nature of engineering (the document is two pages long), it provides a framework that could be used to develop teacher training programs. The standards cover 75% of the aspects identified by experts as being important to K-12 education including *Divergent*, *Creative*, *Iterative*, *Communicative*, and *Collaborative*. For example, the standards provide a list of concepts important to understand in engineering entitled, "Nature, content, and practices of engineering". Under this heading, the authors of the standards note that engineering is creative, team-oriented, uses failure, assumes that multiple solutions are possible, and involves multiple ways of communicating. Although the standards provide no additional detail on these items, they identify similar aspects to the results of the present investigation. Although the standards were not developed using empirical methods, their collaborative development process (using focus groups) gives credibility to teachers using the approach (ASEE, 2014b). By integrating the empirical results of the present investigation into the existing ASEE engineering teacher education framework, a solid foundation can be built for teacher preparation and professional development programs.

Research on optimum pedagogical approach for the nature of science provides guidance for the best approach to developing curriculum to teach the aspects of the nature of engineering. Two major methods have been proposed for teaching the nature of science: Implicit and explicit, as categorized by Abd-el-Khalick and Lederman (2000) in a review of the literature. Implicit methods employ activities that include inquiry or process skills with the goal of helping students to learn about the nature of science without ever discussing its concepts. A contrasting approach employs ways to draw students' attention to tenets of the nature of science by directly discussing the concepts in the course of instruction. Empirical research on these two pedagogical approaches to teaching student about the nature of science have consistently shown that the explicit approach yields better learning outcomes in multiple settings (Bell, Blair, Crawford, & Lederman, 2003; Hanuscin, Akerson, & Phillipson-Mower, 2006; Khishfe & Abd-El-Khalick; 2002). Therefore, it is recommended that instruction and curriculum development for the nature of engineering be developed using an explicit approach.

From an instructional perspective, an explicit approach to teaching the nature of engineering might involve students learning about the aspects in a stand-alone lesson, or contextualized in other engineering content as described in nature of science approaches (Akerson, Nargund-Joshi, Weiland, Pongsanon, & Avsar, 2014). A stand-alone activity might include an activity that was developed with the goal of helping students understand one of the nature of engineering aspects without covering traditional science content. A contextualized activity would cover content already included in the curriculum, but with an emphasis on a particular aspect of the nature of engineering. For example, a chemistry class could include teach students about the *Divergent* aspect of the nature of engineering through a design activity that yielded multiple solutions (See Appendix C). The teacher could ask students to design an object using their knowledge of polymers and bonding. After the students have completed their designs and tested their solutions, the teacher could initiate a discussion about whether there is a right answer to the engineering problem. Students could be assigned to two teams, one arguing that engineering seeks one right answer and the other arguing that engineering allows divergent solutions. The discussion that results could help students understand how the *Divergent* aspect of the nature of engineering allows for multiple solutions that each solve the problem in different ways.

This curriculum example underscores one of the challenges of introducing the nature of engineering in teacher preparation. When learning about the nature of science, pre-service teachers can draw on science experience from their many years of science education. This background makes it easier to help teachers understand the tenets of the nature of science. With engineering, however, pre-service teachers often have little experience. For example, pre-service teachers may have participated many activities that encourages them to investigate natural phenomena, but never had the opportunity to design a technical solution to a problem. In order to develop of understanding of engineering, pre-service teachers need to be able to experience engineering in multiple settings. They need to experience engineering design as an extension of science (by applying scientific principles) as well as a field that has often has different aims than science. As they begin to experience engineering on their own, aspects of the nature of engineering can be linked to the activities they are learning. By building a foundation of engineering knowledge, pre-service teachers can become more comfortable with engineering design and the nature of engineering for the K-12 classroom.

The current research project has the potential to improve teacher education by connecting engineering more clearly to science standards that include engineering. As noted above, the NGSS includes engineering practices and disciplinary content knowledge, but does not address the nature of engineering in any detail. The aspects of the nature of engineering elucidated in the present investigation more clearly define engineering for pre-service teacher education. By linking the supportive language from the Framework (2011) to the aspects of the nature of engineering identified in the present investigation, pre-service teachers can begin see how engineering is both similar and different than engineering.

Finally, the aspects of the nature of engineering described by the experts in the present investigation can serve to inform the development of curriculum for science education programs. Many teacher preparation programs are in the early phases of developing curriculum to support pre-service teacher education in engineering. The aspects outlined in the present investigation have the potential to support these development efforts by clearly defining the nature of engineering and the components of engineering that are useful in a K-12 setting.

Implications for Policy

The nature of engineering concepts developed in the present investigation have the potential to inform future education policy in important ways. As noted above, the NGSS standards include engineering practices and engineering design process practices but do not emphasize the nature of engineering. The emphasis of engineering in the science standards has increased the visibility the field dramatically. However, the integration of engineering practices with science practices has the potential for leaving students confused about the true meaning of engineering. Some students might come to see engineering only as an application of science with similar practices. The inclusion of engineering in the NGSS has made it even more important to include nature of engineering in future policy efforts to ensure students deeply understand engineering as well as science.

With this in mind, it is recommended that the nature of engineering be included explicitly in future state and national science standards efforts. The NGSS has increased the visibility of engineering at the K-12 level but it is important for students to gain a complete view of the field. The nature of science was unfortunately not given a prominent place in the NGSS with an appendix devoted to the topic. In future standard development, it is recommended that the nature of engineering (as well as the nature of science) be included in the science standards themselves. It is difficult for students to understand engineering without understanding the characteristics of the nature of engineering itself.

A similar recommendation is made for including the nature of engineering in future technology standards. These standards were developed in 2007 and do not attempt to integrate engineering into technology education. Given current interest in integrated STEM education, it would be valuable to see engineering included as an integral component of technology education. This is especially true since the ITEEA officially changed its name from the International Technology Education Association (ITEA) to the International Technology and Engineering Education Association (ITEEA) in 2010. Given this new emphasis, it is recommended that future technology standards include extensive coverage of the nature of engineering from an empirical standpoint. The National Academy of Engineering has recommended that engineering be integrated into science and technology standards at the national level rather than be given its own set of K-12 standards (National Academy of Engineering & National Research Council, 2009). This means that engineering must become an integral part of the science and technology standards for students to gain a complete understanding of this field. It falls to future standards work of the ITEEA to implement this vision and make engineering an equal partner to technology in its standards.

Limitations

The findings of the present investigation are the result of tradeoffs made in research design and analysis. This is the case with all research projects. Because Delphi studies are conducted using mixed methodologies, they can be criticized from either the qualitative side or the quantitative side. Because of the use of a mixed-method Exploratory Design (Creswell & Plano-Clark, 2007, p. 75), the present investigation emphasized the qualitative results. As a result of this approach, the results of this Delphi study should be viewed as being representative and transferrable to science and engineering educators in the United States. The constructivist lens used in this investigation recognizes that multiple perspectives are possible. The views on the nature of engineering expressed by the participants of the present investigation are intended to be one perspective that is valuable to the engineering educational field.

From the qualitative perspective, Delphi studies are limited in the type of qualitative data they can collect. Qualitative researchers that utilize face-to-face interviews have the opportunity to ask follow-up questions and ensure that they have an understanding of what the participant is saying. In a Delphi study, the written responses at each round must be interpreted by the researcher without the benefit of follow-up questions. In an ideal world, the researcher would meet each participant face-to-face to discuss their views on the research topic. For a study such as this one, written responses in Round 1 allowed participants to be part of the study without travel and with the flexibility to respond to the questionnaire at their own convenience. One way the Delphi process reduces the potential for not understanding the participant is to provide multiple opportunities to provide feedback to the results of the prior round. In the present investigation, participants were given three opportunities to make comments on the specific results of prior rounds. Through these opportunities for comment, the participant can communicate about the interpretation of prior responses.

From a quantitative perspective Delphi studies are limited because they typically do not randomly sample a population of interest. The present investigation is no exception. The researcher purposively selected candidates for the study based on their involvement in national educational organizations and their expert knowledge of teaching engineering in K-12 contexts. The quantitative results of such a group are valuable in guiding the prioritization and selection of individual aspects during the study, but the intent of the numeric results is not to provide statistical inferences to the larger population of educators. Inference to a larger population is not required to provide results that are credible and transferrable. Given the panel was chosen from multiple groups (teachers of science and engineering at multiple educational levels) and from geographically dispersed locations, the results of this research can be viewed as being useful in many settings. In addition, the use of qualitative methods in the present study provides a richer description of the nature of engineering than would have been developed using a pre-set list of concepts in a quantitative survey.

The method of participant selection in the present investigation had some limitations due to the challenges of identifying experts in the four groups studied. Delphi studies such as Osborne et. al. (2003) invited a small number of well-recognized experts in the field expecting that a majority of them will complete all three rounds of the Delphi process. Indeed, Osborne, et. al. invited 20 experts with national and international repute with extensive publications to participate in his study and all but two completed Round 3 of the study. One limitation in the present investigation is that participants were knowledgeable about engineering education and had PhD degrees or teacher training instead of international repute. One could argue that experts recognized at the national or international level might have a better understanding of the field of engineering education. On the other hand, the field of engineering education is so new that very few experts exist with an international following. The present investigation, therefore, attempted to find teachers and faculty who were knowledgeable in engineering education and used these concepts in their practice. In order to identify individuals that met this criteria, a large number of potential candidate canvassed to participate in the study. Rather than being identified as experts in engineering education prior to invitation, participants were recruited by their membership in professional associations. Participants interested in the study therefore self-reported their level of expertise, education, and knowledge in the field of engineering education. A potential limitation to this approach is that experts selected via this method do not have third-party verification of the background the participant provides to the researcher. However, one of the advantages of a Delphi study is that the concepts provided by individuals in the initial qualitative round are rated by the larger group in later rounds. Through this process, concepts that are not relevant to the topic or are of lower priority to the panel are eliminated from the list of final items. This has the advantage of removing concepts from the list that might have been proposed by participants who were either not educated in the K-12 engineering education field, or who did not have the expertise they claimed they did.

In addition, because it was assumed that there was a potential that a large percentage of the participants could drop out of the study between Round 1 and Round a large panel of 100 participants was selected for participation in the Round 1 survey. One of the issues with large panels in Delphi studies is that participants have a difficult time reaching consensus (Hogarth, 1978). In the present investigation, achieving consensus did not appear to be an issue, but some aspects showed instability. It is possible that the large panel size increased the number of comments between rounds and encouraged panel members to change their mind, decreasing stability. It was important to ensure that at least 30 participants completed all three rounds of the study. This would provide at least seven participants from each group. While it is possible that the larger panel size made it more difficult to reach stability on some aspects, completing the survey with approximately 15 participants from each group increased the richness of comments provided through the entire process, yielding more complete results than a smaller group.

Despite these potential limitations to the present investigation, there is an argument to make for the usefulness of the results. This study gathered input from a diverse set of experts that included science teachers, engineering/technology teachers, science education faculty and engineering education faculty. Each of these participant groups has their own unique views on the nature of engineering. Aspects that achieved both consensus and stability have the potential for being useful not only in

K-12 science education but also in K-12 engineering/technology education. In addition, of the 65 panel members that completed the Round 1 survey, 92% completed both Rounds 2 and 3. This indicated a high level of engagement in the topic and provided consistency in the participants that provided comments to the entire panel in Rounds 2 and 3. Thus results and conclusions of the present investigation are supported by the repeated feedback of 60 panel members who completed all three rounds of the Delphi process.

Future Research

Research on the nature of engineering needs to be conducted on three fronts. First, the K-12 nature of engineering concepts developed in the present investigation would be strengthened through additional empirical studies. For example, other methods could be employed (such as focus groups or other group processes) with additional participants to identify important nature of engineering concepts for K-12 education. While a single Delphi study provides a valuable foundation to a growing field, multiple studies provide additional perspectives on which to base future policy and curriculum.

Second, it will be important to understand current teacher and student perspectives on the nature of engineering. As discussed above, current work on teacher views of the nature of engineering are limited and open-ended. The results from the present investigation can guide the development of a robust instrument that can be used to understand what views students and teachers have on the nature of engineering. Development of such an instrument could be based on the extensive research undertaken with the Views of the Nature of Science Questionnaire (VNOS) and could implement shorter-form versions (D and E) developed more recently (Lederman, et al. 2002; Lederman, 2007). Since very little research has been conducted on this topic, future research in this area has the potential to greatly impact the development of teacher preservice and teacher professional development programs. Because most K-12 teachers have very little exposure to engineering in the course of their education it is important to determine what views they hold about the nature of engineering. Results of this type of research could be used to create professional development programs that increase teacher understanding and comfort level with engineering.

A final area of research that would be valuable to conduct is empirical evaluation of existing engineering standards and curriculum for nature of engineering content. It would be useful to understand how existing state and national standards treat the nature of engineering. A number of engineering curriculum programs are being used nationally to improve engineering understanding in the K-12 classroom. It will be important to understand how they present the nature of engineering in light of the results of the present investigation. Empirical research in these areas will be important so that future policy and curriculum efforts can be developed to help students understand engineering from a broader perspective.

Studying the nature of engineering for K-12 education is valuable for better understanding how to teach this relatively new subject in the classroom. The NGSS and state standards have begun asking classroom teachers to teach students basic design and engineering concepts. Research on what to teach and how to teach it has been sparse. Previous projects have relied on literature reviews (Karatas 2009), group discussions (NGSS, 2011), and formal focus groups (ASEE, 2014b) to describe the nature of engineering. The present investigation convened a group of 100 experts in K-12 engineering education to determine which aspects of the nature of engineering were important for student to learn. The results of this study can inform policy makers as they try to determine which areas of the engineering field are appropriate for K-12 students to learn. Curriculum developers and classroom teachers may use the results of the present study to create activities and lead classroom discussions that help students understand the nature of engineering better. The end goal of these activities is to improve students understanding of engineering as a discipline and help them to become more engineering literate as they become productive citizens in an increasingly engineered world.

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APPENDICES

Appendix A – Communication Letters to Panelists

Recruitment -- Email Letter

Title: Research on Engineering in K-12 Settings

Dear Participant Name,

I am asking you, as an expert in [Insert Field: engineering education or science education] to participate in a research project designed to create a description of the nature of engineering for use by STEM educators. We are both members of [Insert Field: ITEEA, NSTA, NARST, ASEE] Association.

Engineering is now part of the K-12 curriculum standards in many states. This investigation will help clarify the characteristics of engineering in K-12 settings and improve the teaching of engineering in the STEM curriculum.

The investigation will consist of four surveys (spread over the upcoming weeks) that should take approximately 15 minutes each. No travel is required. Not everyone who provides initial information will be asked to participate on the expert panel. Please respond by 11/17.

Follow this link to the Survey:
Link

Thank you for considering this initiative. Please contact us if you have any questions.

Brian Hartman, MAT
Science Education Doctoral Candidate

Randy Bell, PhD
Associate Dean, College of Education
Oregon State University

If the link above doesn't work, you may also copy and paste the URL below into your internet browser:
Survey_URL

Follow the link to opt out of future emails:
Unsubscribe_URL

Round 1 Email Letter

Nature of engineering survey for: [Insert Field: Participant Name] Due 12/11

Dear [Insert Field: Participant Name],

Thank you for responding to the invitation to be involved with the K-12 nature of engineering investigation at Oregon State University. You have been selected to participate on the panel of experts.

The purpose of this research is to elicit the opinions of experts and attain consensus regarding important characteristics of the nature of engineering in K-12 settings. The results will be used to develop framework for use at the high school level. Each round should last two to three weeks. **Please respond by December 11.**

Follow this link to the Survey (three questions):
Survey_Link

Thank you,

Brian Hartman
Doctoral Candidate
Science Education

If the above link does not work paste the URL below into your internet browser:
Survey_URL

Follow the link to opt out of future emails:
Unsubscribe URL

Round 2 Email Letter

Nature of engineering survey, Round 2: [Insert Field: Participant Name] Due JAN 19

Dear [Insert Field: Participant Name],

Thank you for responding to Round 1 of the K-12 nature of engineering investigation at Oregon State University. We have analyzed the results from Round 1 and developed a list of 25 themes that attempt to capture the collective ideas of the group.

In this survey you have the opportunity to rate the importance to each item from the previous survey. The survey should take about 15 minutes. **Please respond by January 19.**

Follow this link to the Survey:
Survey URL

Thank you,

Brian Hartman
Doctoral Candidate
Science Education

If the above link does not work paste the URL below into your internet browser:
Survey_URL

Follow the link to opt out of future emails:
Unsubscribe URL

Round 3 Email Letter

Nature of engineering survey, Round 3: [Insert Field: Participant Name] Due FEB 10

Dear [Insert Field: Participant Name]

Thank you for responding to Round 2 of the K-12 nature of engineering investigation at Oregon State University. We have analyzed the results from Round 2 and developed a list of 15 themes that attempt to capture the collective ideas of the group.

In this survey you have the opportunity to rate the importance to each item from the previous survey. The survey should take about 15 minutes. **Please respond by February 10.**

Follow this link to the Survey:
Survey URL

Thank you,

Brian Hartman
Doctoral Candidate
Science Education

If the above link does not work paste the URL below into your internet browser:
Survey URL

Follow the link to opt out of future emails:
Unsubscribe URL

Reminder Email Letter

Nature of engineering survey, Round X: [Insert Field: Participant Name] Due Date

Dear [Participant Name],

Thank you for participating in Round X of our investigation on the nature of engineering.

Due to the interdisciplinary nature of the engineering education field, your opinion as an expert is crucial for the success of this project. To continue participating as a member of the panel, please respond by Due Date.

Follow this link to the Survey:
Survey Link

Thanks,

Brian Hartman
Doctoral Candidate
Oregon State University

Or copy and paste the URL below into your internet browser:
Survey Link

Follow the link to opt out of future emails:
Unsubscribe Link

Appendix B – Survey Questions

Invitation -- Questionnaire

Nature of Engineering Delphi Investigation Thank you for joining our pool of science and engineering education experts. The purpose of this investigation is to determine your views on the nature of engineering for use in K-12 settings. This investigation is not designed to benefit you directly, however, the results may be used to improve the field of engineering education. The investigation is being conducted as part of doctoral dissertation research. Only the researchers will know the identity of participants and their responses. Although we employ standard processes to ensure the data you provide on this survey is secure, the security and confidentiality of information collected from you online cannot be guaranteed. There is a chance that your name could be disclosed accidentally. Confidentiality will be kept to the extent permitted by the technology being used. Information collected online can be intercepted, corrupted, lost, destroyed, arrive late or incomplete, or contain viruses. This investigation is completely voluntary and you may withdraw at any time; however, the best results are obtained from participants who follow through to completion of the investigation. Not all participants will be selected for participation in the investigation and data for these individuals will not be used in this investigation or future studies.

Your Name

Job Title

Organization or Affiliation

Email

Phone Number

Which of the following most closely represents your work background?
- ❍ Science Educator -- K-12 level
- ❍ Engineering / Technology Educator -- K-12 level
- ❍ Science Educator -- University level
- ❍ Engineering Educator -- University level

How many years have you taught or developed curricula for K-12 science or engineering/technology classes?
- ❍ Zero to two years
- ❍ Three to five years (3 yrs = minimum requirement to participate)
- ❍ Six to ten years

- ❍ Eleven to twenty years
- ❍ More than twenty years

Have you taken courses or professional development programs that included K-12 engineering topics? (Required)

- ❍ Yes
- ❍ No

Have you used engineering methods or topics in your K-12 classes/curricula (required)?

- ❍ Yes
- ❍ No

Please describe additional expert qualifications you have in the field of K-12 engineering education (e.g. publications, conference presentations, grants, curricula, teaching experience, employment, etc.)

Additional information about the Delphi survey process Round 1 the initial survey, will consist of one open-ended question. Round 2 will consist of a series of questions that will allow you to rate the importance of concepts submitted by panel members in Round 1. Round 3 will consist of a series of questions that will allow you to rate the importance of concepts submitted by panel members in Round 2.

Thank you for being willing to participate in this investigation. By submitting this survey, you are agreeing to be considered for participation in the survey

Brian Hartman Doctoral Candidate, Science Education Oregon State University hartmanb@onid.oregonstate.edu

Randy Bell, PhD Principal Investigator, Associate Dean College of Education Oregon State University Randy.Bell@OregonState.edu Phone: (541) 737-4661

Round 1 -- Questionnaire

Nature of Engineering Delphi Investigation -- Round 1 of 3
Thank you for your willingness to participate in our survey. This questionnaire consists of one open-ended question. Your responses will be consolidated with those of a broad range of experts to identify the engineering concepts that are appropriate for K-12 students to learn about the nature of engineering. Your specific responses will remain de-identified.

In this investigation, the nature of engineering, refers to engineering as a way of knowing as well as the nature of engineering knowledge. It includes perspectives on engineering from fields including history, sociology, anthropology, and philosophy (epistemology).

Open-ended Question Please list all the characteristics of the nature of engineering that are important for K-12 students to know. The nature of engineering refers to engineering as a way of knowing as well as the nature of engineering knowledge. Please provide a brief description and/or explanation for each item. There is no limit to the number of items you may list.

What K-12 grade levels have you PRIMARILY worked with (teaching, curriculum, or research)?

- ❍ Grades kindergarten to five
- ❍ Grades six to eight
- ❍ Grades nine to twelve

Would you like to be recognized as a member of the expert panel after all survey rounds have been completed?

- ❍ Yes
- ❍ No

How would you like your name to appear in print?
Name (1)
Title (2)
Organization (3)
Thank you for participating in the first round of this Delphi investigation. Your results will be collated with others. In the next round (in 2-3 weeks) you will have an

opportunity to express your opinion regarding which of these concepts are most important. If you have any questions about this investigation, please contact:

Brian Hartman Doctoral Candidate, Science Education Oregon State University hartmanb@oregonstate.edu

Round 2 -- Survey

Thank you for participating in Round 1 of the K-12 nature of engineering investigation. Your responses were collated with those of other participants and coded for themes. The resulting list includes 19 concepts for potential inclusion as characteristics of the nature of engineering. You will also be given the opportunity to add additional concepts that you believe should be included on the list. Your responses will be shared anonymously with the panel in Round 3.

Q2 Please rate the following items (a total of 19 questions) for their importance to K-12 education using the scale 1=not important to 5=very important. Add a justification or clarification for any item as needed by referencing its title in the comments section below.

	Not importan t (1)	Slightly importan t (2)	Moderatel y important (3)	Importan t (4)	Very importan t (5)
Accessible to everyone Engineering knowledge has been created by many cultures, making it diverse and accessible to everyone. (1)	❍	❍	❍	❍	❍
Collaborative Engineering work is typically a team effort with knowledge spread among many people. (22)	❍	❍	❍	❍	❍
Contextual Engineering solutions are dependent on the local issues and situations for which they are developed. (4)	❍	❍	❍	❍	❍
Creative Engineers often use creativity when developing solutions to problems. (2)	❍	❍	❍	❍	❍
Design Process Engineers follow a semi-structured process to develop technical solutions that may involve iterative cycles of design, testing, and improvement. The steps of the process vary by discipline and situation. (6)	❍	❍	❍	❍	❍

Develops Products, Processes, and Protocols Engineers develop physical products that are part of the built world. They also create other types of outputs such as processes and protocols. (27)	❍	❍	❍	❍	❍
Distinct from Science The field of engineering is distinct from science. However, it uses science as a tool and works within scientific principles. (8)	❍	❍	❍	❍	❍
Ethical Engineers have ethical responsibilities. While engineering often follows the ethics of utility (greatest benefits given the costs), engineers also consider the negative consequences of designs such as impacts to minority groups and the environment. (11)	❍	❍	❍	❍	❍

Evaluates Against Criteria Engineering designs are evaluated against criteria such as economic feasibility, performance, risk of failure and government regulation. This involves trade-offs between the constraints to find the best solution. (5)	❍	❍	❍	❍	❍
Historical Engineers understand not only the current ways to solve a problem, but also the historical development of engineering and the technologies it creates. (12)	❍	❍	❍	❍	❍
Involves Systems Thinking Engineering often requires a way of thinking that emphasizes the ability to understand how the parts of a system work together (systems thinking). (21)	❍	❍	❍	❍	❍
Involves Communication Engineering requires communication between team members and other stakeholders. (3)	❍	❍	❍	❍	❍

Iterative Engineers often expect their initial designs to fail. They use these early failures to learn what went wrong and improve the design. (15)	❍	❍	❍	❍	❍
Multidisciplinary Engineers use science, mathematics, technology and other disciplines to develop solutions to problems. (17)	❍	❍	❍	❍	❍
Problem Focused The goal of engineering is to solve problems that meet perceived needs and wants. (29)	❍	❍	❍	❍	❍
Tentative Solutions There is rarely one right answer to engineering problems. Instead, the usefulness of a solution determines its value. (23)	❍	❍	❍	❍	❍
Inclusive of Multiple Disciplines Engineering is not one fixed entity. There are many types of engineering (e.g. biological, chemical, civil, electrical, mechanical, etc.), each with their own unique approach to the field. (24)	❍	❍	❍	❍	❍

User Focused Engineering is influenced by the context of the solution so empathy for the user is important to the design process. (20)	❍	❍	❍	❍	❍
Uses Modeling Engineering develops models (mathematical, visual, or physical) to support testing and reduce the risks of building full-scale items. (16)	❍	❍	❍	❍	❍

Q3 Add a justification or clarification for any item as needed by referencing its title of the question in the comments section below. Your responses will be provided to participants in Round 3.

Q4 Please add any additional characteristics of the nature of engineering that were not captured in the list of items above.

Round 3 -- Survey

Nature of Engineering Delphi Investigation Final Round   Thank you for participating in Round 2 of the K-12 engineering Delphi investigation. Your responses were collated with those of other participants and the lowest-rated items removed.   The resulting prioritized list includes 15 concepts that the panel believes are important to K-12 nature of engineering. Three concepts (Accessible to everyone, unique disciplines, and historical) were removed because of their low ratings (rated below 4.0 or mode less than 5.0). One (user focused) was combined with another item (contextual).   Please rate the following items (a total of 15 questions) for their importance to K-12 nature of engineering using the scale 1=not important to 5=very important. They are listed in random order. Review the results and comments from Round 2 to guide your choice. Add comments or clarifications for any items as needed. Your responses will be used in the final analysis.

Survey Start   Please rate the following items (a total of 15 questions) for their importance to K-12 nature of engineering using the scale 1=not important to 5=very important. Review the results and comments from Round 2 to guide your choice. Add comments or clarifications for any items as needed

Creative. Engineers often use creativity throughout problem identification, design, implementation, and communication processes.   Results   Mean: 4.40   SD: 0.75   90% of panelists rated 4.00 or above.   (Important or very important)   Summary of Comments   Creativity is very important to engineering education. Creativity, collaboration, and communication are important to most jobs. Engineering involves both creativity and logical thinking.

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Creative	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Ethical. Engineers have ethical responsibilities. While engineering often follows the ethics of utility (greatest benefits given the costs), engineers also have a duty to consider the negative consequences of designs such as impacts to minority groups and the environment. Results Mean: 4.38 SD: 0.77 83% of panelists rated 4.00 or above. (Important or very important) Summary of Comments Engineers aren't often in a place where they can make ethical decisions. They do what they are told to do to keep their jobs. We shouldn't hide this from our students.

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Ethical	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Tentative Solutions. There is rarely one right answer to engineering problems. The solution to an engineering problem is but one attempt to meet specifications while staying within constraints. Other successful solutions are possible. Results Mean: 4.52 SD: 0.74 89% of panelists rated 4.00 or above. (Important or very important) Summary of Comments Tentative solutions also depends on how well the options meet specifications or constraints. This is particularly important in schools where students are guided to the "Right Answer".

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Tentative Solutions	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Different than Science. The field of engineering is different than the field of science. It primarily seeks practical solutions to human problems whereas science asks questions about nature. Engineering uses some of the same practices as science and applies scientific principles. Results Mean: 4.02 SD: 1.01 95% of panelists rated 4.00 or above. (Important or very important) Summary of Comments Engineering is applied rather than pure science. Engineer and science are not distinct but connected to on another. You can't have one without the other. We need to understand the natural interconnectedness of engineering and science.

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Different than Science	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Collaborative. Engineering work is typically a team effort with input and knowledge spread among many people with varied expertise. Results Mean: 4.52 SD: 0.64 95% of panelists rated 4.00 or above. (Important or very important) Summary of Comments This theme should be ranked lower because it is not unique to engineering. Collaboration, creativity, and communication are not unique to engineering. They are important for almost any job today.

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Collaborative	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Evaluated Against Criteria. Engineering designs are evaluated against criteria such as economic feasibility, performance, risk of failure, public interests, and government regulation. Results Mean: 4.52 SD: 0.67 94% of panelists rated 4.00 or above. (Important or very important) Summary of Comments It is time that we always include social/environmental impacts (or sustainability) among the criteria we use for evaluation.

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Evaluates Against Critaria	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Multidisciplinary. Engineers use science, mathematics, technology and other disciplines to develop solutions to problems. Results Mean: 4.44 SD: 0.78 86% of panelists rated 4.00 or above. (Important or very important) Summary of Comments This theme is already known by students. This topic doesn't need to be addressed by 9-12 students. Additional disciplines should be added such as history, social studies, economics, psychology, writing, art, communication, etc.

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Multidisciplinary	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Design Process. Engineers follow a semi-structured process to develop technical solutions that may involve iterative cycles of design, testing, and improvement. The steps of the process may vary by discipline and situation. Results Mean: 4.54 SD: 0.78 89% of panelists rated 4.00 or above. (Important or very important) Summary of Comments The engineering design process is more universal across different disciplines than is indicated in this theme. The Engineering Design Process is similar to the Scientific Method. This is not a good thing.

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Design Process	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Con**textual.** Engineering solutions are dependent on the issues and situations for which they are developed. Engineering is influenced by the context of the solution so understanding the user is important to the design process. Culture and language are part of the context along with government, geography, and economic systems. Results Mean: 4.05 SD: 0.87 76% of panelists rated 4.00 or above. (Important or very important) Summary of Comments None

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Contextual	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 please provide a justification for your response.

Please add any additional comments or clarifications below.

Involves System Thinking. Engineering often requires a way of thinking that emphasizes the ability to understand how the parts of a system work together (systems thinking). Results Mean: 4.37 SD: 0.77 75% of panelists rated 4.00 or above. (Important or very important) Summary of Comments None

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Involves System Thinking	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Learns from Failure. Engineers often expect their initial prototypes to fail. They analyze these early failures to learn what went wrong and improve the design so the final solution can be successful. Results Mean: 4.38 SD: 0.81 83% of panelists rated 4.00 or above. (Important or very important) Summary of Comments Learning from trial and error is very important in engineering and science education. Engineers learn from previous engineering failures. This is part of the iterative process. Iteration is an important part of K-12 engineering education.

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Learns from Failure	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Develops Products, Processes, and Protocols. Engineers develop products, and other types of outputs such as processes, and protocols. Results Mean: 3.92 SD: 1.07 68% of panelists rated 4.00 or above. (Important or very important) Summary of Comments The issue with this statement is that it infers the "built world". This builds a dichotomy between nature and the products of engineering. Children may think that the "built world" is separate from nature and has no interdependence with nature.

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Develops Products, Processes, and Protocols	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Problem Focused. 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. Results Mean: 4.62 SD: 0.58 95% of panelists rated 4.00 or above. (Important or very important) Summary of Comments One respondent does not agree with the word "perceived" in the theme statement. The idea that engineering is to improve the quality of life for people should be included. 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.

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Problem Focused	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Involves Communication. Engineering requires communication between team members and other stakeholders. Results Mean: 4.46 SD: 0.71 90% of panelists rated 4.00 or above. (Important or very important) Summary of Comments This theme needs to include the standard way to write up engineering solutions. This is very different form general English and social science writing. Communication is not unique to engineering. However, communication with colleagues and communication with clients/stakeholders is critical. Collaboration, creativity, and communication are important to most jobs today.

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Involves Communication	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

Uses Modeling. Engineering develops models (e.g. mathematical, visual, or physical) to support design, testing and implementation to reduce the risks of building full-scale items. Results Mean: 4.37 SD: 0.79 84% of panelists rated 4.00 or above. (Important or very important) Summary of Comments None

	Not Important (1)	Slightly Important (2)	Moderately Important (3)	Important (4)	Very Important (5)
Uses Modeling	❍	❍	❍	❍	❍

If you rated this theme a 1, 2 or 3 please provide a justification for your response.

Please add any additional comments or clarifications below.

K12 Nature of Engineering Survey Completion
Thank you for participating in the three rounds of the Delphi investigation. Your valuable input will be used to inform teacher practice, develop K-12 engineering curriculum, and guide further research.

Following is a summary of the 15 concepts rated most highly. Important K-12 Characteristics of the Nature of Engineering
Creative
Ethical
Tentative Solutions
Different than Science
Collaborative
Evaluated Against Criteria
Multidisciplinary
Design Process
Contextual
Involves System Thinking
Learns from Failure
Develops Products, Process, and Protocols
Problem Focused
Involves Communication
Uses Modeling

Please use the following space to provide any additional feedback on the results or the process.

Round 4 -- Questionnaire

Nature of Engineering Delphi Investigation Final Feedback Thank you for participating in Round 3 of the K-12 engineering Delphi investigation. Your responses were collated with those of other participants and the lowest-rated items removed.

The resulting prioritized list includes eight concepts that the panel believes are most important to K-12 nature of engineering. Two concepts (problem focused and develops products, processes, and protocols) were removed because of their low ratings (average rating lower than 4 -- 'important') and five concepts had sufficient ratings but changed dramatically between Rounds 2 and 3. This survey will provide a preview of the final list of themes as well as give you the opportunity to provide a summary statement about the nature of engineering.

Survey Start As a member of the panel who has completed all three rounds of the Delphi investigation, you are in a unique position to provide a summary statement about the nature of engineering for K-12 education. The nature of science is often delineated in two complementary ways: Succinct definition and a List of tenets: For example, the tenets of the nature of science include tentativeness, theory-laden, empirical, etc. We have been hard at work developing aspects of the nature of engineering resulting in 13 tenets. We have yet to develop a succinct definition of the nature of engineering. After participating in the full Delphi investigation on the nature of engineering, you are uniquely prepared to help develop a succinct definition / delineation of the term nature of engineering.

How would you succinctly define the term nature of engineering?

Following is the final list of nature of engineering themes ordered by average rating. Please select the earliest grade level that you believe each theme would optimally be introduced. Add a justification or clarification for any item as needed by referencing its title in the comments section below. This feedback will be used to make final edits to each item.

	K-2 (1)	3-5 (2)	6-8 (3)	9-12 (4)
Multiple Solutions The solution to an engineering problem is but one attempt to meet criteria while staying within constraints. There is rarely one right answer to engineering problems. Other successful solutions are possible. (35)	❍	❍	❍	❍
Creative Engineers use creativity in addition to logical thinking throughout problem identification, design, implementation, and communication processes. (37)	❍	❍	❍	❍
Learns from Failure Learning from failure is important to engineers because early designs often do not meet criteria and constraints. They analyze these early failures to identify issues and improve the design so the final solution can be successful. (4)	❍	❍	❍	❍
Uses Modeling Engineering develops models (e.g. mathematical, visual, or physical) to support design, testing and implementation to reduce the risks of building full-scale items. (2)	❍	❍	❍	❍
Requires Communication Engineering requires communication between team members and other stakeholders. (6)	❍	❍	❍	❍

Criteria and Constraints Engineering designs must meet constraints (such as economic, environmental, social, safety, etc.) and are evaluated against criteria (such as economic feasibility, performance, risk of failure, public interests, etc.). (38)	❍	❍	❍	❍
Collaborative Engineering work is typically a team effort with input and knowledge spread among many people with varied expertise. (8)	❍	❍	❍	❍
Unique Way of Knowing Engineering expands its knowledge through empirical tests, experience, and applying science and mathematics. These processes are related to but distinct from the way science expands knowledge. Science begins with questions about phenomena in the natural world, whereas engineering begins with defining a problem in need of a solution.	❍	❍	❍	❍

The following items were highly rated (average rating greater than 4 - 'important') but a large number of participants (greater than 15%) changed ratings on these items between Rounds 2 and 3. They will be included in the final list, but will be shown as

	K-2 (1)	3-5 (2)	6-8 (3)	9-12 (4)
Involves Systems Thinking Engineering often requires a way of thinking that emphasizes the ability to understand how the parts of a system work together (systems thinking). (35)	❍	❍	❍	❍
Design Process Engineers follow a semi-structured process to develop technical solutions that may involve iterative cycles of design, testing, and improvement. The steps of the process may vary by discipline and situation. (37)	❍	❍	❍	❍
Multidisciplinary Engineers use science, mathematics, technology and other disciplines to develop solutions to problems. (4)	❍	❍	❍	❍

Ethical Engineers have ethical responsibilities. While engineering often follows the ethics of utility (greatest benefits given the costs), engineers also have a duty to consider the negative consequences of designs such as impacts to underserved groups and the environment. (2)	❍	❍	❍	❍
Contextual Engineering solutions are dependent on the issues and situations for which they are developed. Engineering is influenced by the context of the solution so understanding the user is important to the design process. Culture and language are part of the context along with government, geography, and economic systems. (6)	❍	❍	❍	❍

Add a justification or clarification for any item as needed by referencing its title of the question in the comments section below. Your responses will be useful in preparing the final wording of each theme.

Please provide any additional feedback on final results or the Delphi process.

Appendix C –Nature of Engineering Activity

Fork it over -- Design a Biodegradable Utensil

Objectives

- Understand the factors that affect biodegradation in materials
- Understand chemical bonding and its effects on the strength of materials
- To develop new biodegradable forms of plastic
- Optimize materials to develop a viable product
- Find ways to remove non-biodegradable products from the waste stream
- To better understand the Divergent aspect of the nature of engineering

Skill Level: Middle school and High school	**Prep time:** 10 min. **Class time:** 45-60 minutes depending on the number of experiments. Bioplastics may take up to a week to cure. Additional time may be required to improve the design.

Materials (per group)

- Tap water
- Non-stick spray bottle (Pam)
- 2 T ea. bio-based substrates:
  - Corn Starch
  - Unflavored Gelatin
  - Agar Agar
- 1 T plasticizer (glycerin or sorbitol)
- 2 feet of aluminum foil
- Supply of clear plastic cups (So the mixture is visible in the microwave)
- Supply of plastic spoons (For measuring)
- Supply of plastic straws (For stirring)
- Medicine dropper (for measuring plasticizer)
- Measuring spoons (1/4 t, 1/2 t, 1 t)
- Measuring cup (1/4 cup for water)
- Microwave

Next Generation Science Standards

Disciplinary Core Idea:

PS1.A: Structure and Properties of Matter
ETS1.B: Developing Possible Solutions

Performance Expectations:
MS-PS1-2. Analyze and interpret data on the properties of substances before and after the substances interact to determine if a chemical reaction has occurred.
MS-ETS1-4. Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.

HS-PS1-5. Apply scientific principles and evidence to provide an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs.

HS-ETS1-3. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics, as well as possible social, cultural, and environmental impacts.

Practices	Crosscutting Concepts
☐ Asking questions / defining problems	☐ Patterns
☐ Developing / using models	☐ Cause and effect: Mechanism / explanation
☒ Planning / carrying out investigations	☐ Scale, proportion, and quantity
☐ Analyzing / interpreting data	☐ Systems and system models
☐ Math / computational thinking	☐ Energy / matter: Flows, cycles, conservation
☒ Constructing explanations / design solutions	☒ Structure and function
☐ Engaging in argument from evidence	☐ Stability and change
☐ Obtaining / evaluate / communicate	

Background Information

Plastics play an important role in our daily lives. On average, Americans collectively use 2,500,000 plastic bottles every hour, but few of these bottles are recycled or reused. Many of the plastic bottles that we use today are not biodegradable. Biodegradable means that a certain material is capable of being decomposed, or broken down. Plastics are also used in schools, hospitals, homes, grocery stores, restaurants, businesses, research labs, and many other places. Just look around for a minute and you'll see how many things are made of plastic!
Plastics were used all the way back to Roman times with the use of natural resins such as amber and shellac. Native Americans even used plastics to make ladles and utensils out of natural materials. Commercialization of bioplastics started to happen in the 1800s when John Wesley Hyatt Jr. developed an alternative for ivory billiard balls. His products were later found to be flammable and not a successful alternative. In the 1920s Henry Ford used soybeans to manufacture automobiles. Soybeans were used in a number of parts like steering wheels, trim, and dashboard panels. Today, in the United States alone there are over 20,000 facilities that employ over 1.5 million workers and ship over $300 billion in plastic products each year. Unfortunately, most of this plastic is not biodegradable.
Standard plastics cause many problems in the environment. Some types of standard plastics degrade faster than others, but depending on the type of plastic, it may never break down. Much of it goes to landfills, but it can also end up on the side of the road, in waterways, and different places in our environment. This is becoming a huge problem for our wildlife, as it is very detrimental and can destroy habitats for us and other organisms.
Scientists are exploring ways to make plastics better for the environment by making them able to disintegrate naturally. One way of doing this is creating a plastic that biodegrades rapidly. Microbes are able to digest materials if they can break the bonds between the elements. Unfortunately, petroleum-based plastics are bonded using a carbon-carbon bond, something the microbes have not evolved to break. Natural compounds contain peptide bonds (between nitrogen and carbon) and carbon – oxygen bonds that microbes are very capable of breaking. When making biodegradable plastics that are microbe friendly, the trade-off is that the plastic may not be as strong. This may not be a big problem depending on the product. If a car were made with biodegradable parts, it might not last very long. When it comes to disposable utensils, like forks and knives, it is possible to make products that are strong enough to be useful, but still be biodegradable.

Figure 1. Biodegradation of a plastic bottle. Ref.

Bioplastic can be categorized into three different types: Degradable, biodegradable, and compostable. The difference between the three is how long it takes for them to break down. Degradable plastic is just something that breaks down into smaller plastic pieces through a process called oxo-degradation. A chemical is added to standard plastic that breaks down in the presence of oxygen. After the plastic is thrown away, oxygen begins to break down the additive. However, the plastic gets to a point where it is just really small but cannot break down anymore; even microorganisms cannot break it down. This is the difference between degradable and biodegradable plastics. Microorganisms can break down biodegradable plastics into compounds that can be used for plant and animal nutrition through a process of either hydro-degradation or photo-degradation. Hydro-degradation requires water to break down the plastic for microbes and photo-degradation required sunlight. First, microbes break down the carbon-nitrogen or carbon-oxygen bonds in the chains of the polymer so the materials can actually participate in the creation of other organic molecules. Therefore, the bioplastic is broken down and participates in the carbon cycle. Compostable products are a little more vague. By definition compostable products degrade in a reasonable time in a compost pile. For example, 60% of the material has to degrade in 180 days. Despite the type of degradation that occurs, it is valuable to have products that can become part of the natural carbon cycle.

The challenge is to find ways to eliminate plastic forks from the waste stream that do not degrade. In this activity students will play the role of a chemical engineer to design a bioplastic material that could be used for biodegradable utensils. The challenge is to use this knowledge create a biodegradable plastic that is still capable of having tensile strength. The handle of a fork experiences high force when used to cut food. This activity focuses on developing a material that would be best for this use. Students need to remember that the plastics they develop in the lab may not have the strength that a commercial material would have. On the other hand, they should keep good notes because a college student developed a formula for a bioplastic that was purchased by an industrial company for $100,000. They might stumble upon a formula that works better than anything on the market.

Nature of Engineering

In addition to the goals of helping students understand chemical bonding and simple polymers, this activity can be used to teach students about the nature of engineering. The nature of engineering describes engineering as a way of knowing. The nature of engineering can be described through five aspects: Design-driven, Divergent, Iterative, Model-driven, Constrained by Criteria. Because student develop multiple designs of the biodegradable fork in this activity, students can be exposed to the Divergent aspect of the nature of engineering at the end of the activity. Engineering problems can have multiple solutions and still meet the needs of stakeholders. Because science is often taught with the unspoken assumption that science has a right answer, and engineering result with multiple solutions might be challenging for students to internalize. This is a good point to introduce students to the concept of criteria and constraints. An engineering design will often need to achieve certain performance goals or criteria (e.g. a car that travels at a certain maximum speed) while staying within a set of limitations or constraints (e.g. under a certain price). If students can identify the criteria and constraints they were given in this activity, they can begin to understand that there may be multiple fork design that can meet the needs of customers.

Engage

Students should be interested in knowing about the different types of plastic they use every day. The type of plastic can greatly determine one's carbon footprint. Many plastics end up in landfills and could stay there for years to come if they do not biodegrade. Inventors and scientists are trying to make anything that can be disposed of, biodegrade quickly. This can include napkins and to-go containers (like this company EcNow Tech) or even sunglasses. The more products that biodegrade the better. Students may be able to apply their plastic design to other products and continue this biodegradability trend. Developing an inexpensive, usable biodegradable plastic is one of the great challenges of the modern era.

Explore

Experiment Questions:

1. Which chemical process (formula) produces the best bioplastic to make a fork handle?
2. Is there one material that marries durability and strength well?

3. Which material is most cost effective?

Procedure:

Build a mold

1. Create sixteen (16) molds with the aluminum foil in the shape of a fork handle. This could be as simple as a small container about 1 cm wide, 2 cm tall and 10 cm long. The mold should be sealed so that liquids will not leak out.
2. Spray the mold with non-stick spray
3. Number each mold with a Sharpie marker to keep track of the experiment

Bioplastic

1. For each of the following trials, mix warm water, substrate, and glycerin in a clear plastic cup using the following proportions:

Trial	Water	Substrate	Glycerin
Gelatin	¼ cup	12 g (4 tsp.) gelatin	0.5 g glycerin (5 drops)
Agar agar	¼ cup	3 g (1 tsp.) agar agar	0.25 g glycerin (3 drops)
Cornstarch	¼ cup	9 g (3 tsp.) cornstarch	0.5 g glycerin (5 drops)

2. Mix each cup thoroughly until there are no clumps
3. Place a piece of paper or plastic on the floor of the microwave to protect against spills.
4. Heat each mixture separately in a microwave until it begins to froth. This can be accomplished without boiling over by carefully watching the mixture through the microwave window.
5. Stir the mixture with a straw
6. Pour the mixture into three or four molds. Attempt to pour the plastic the same thickness (about 0.5 to 0.75 cm).
7. Allow the mixtures to dry in a warm place. This may take 3-5 days.
8. Test and record the following material characteristics of each bioplastic:
    a) Color, opacity (can you see light through the material), flexibility [(1) cracks (2) stiff (3) somewhat flexible (4) very flexible]
    b) Freeze a sample (to simulate winter). Rate the material for flexibility.
    c) Heat a sample to 120 degrees under a lamp or in an oven (to simulate summer). Rate the material for flexibility
    d) Stain test: Place a drop of coffee and mustard on the plastic. Does the plastic stain?

e) Tensile strength: Hold the plastic sample by one end. How many pennies can you tape on before it breaks? Add pennies one at a time. Add larger weights if the material is strong enough.

9. Choose the substrate that you think will provide the best strength for a fork handle. If the initial experiments don't work well, remind the students that the formula must be optimized for each brand of substrate. Repeat the experiment making adjustments they think will improve the material.
10. (Advanced) Repeat the experiment one or more times using the chosen substrate by adjusting the amount of plasticizer added to the recipe. Ask the students to determine what they think the role of plasticizer is in the recipe. (Teacher Note: Add more plasticizer if the material needs to be more flexible, reduce plasticizer if the material needs to be more solid). The amount of substrate can be adjusted and substrates can be mixed to develop the ideal mixture.
11. After all experiments have been completed, ask the students to make a recommendation for the process that would produce the best plastic for a fork handle. In an ideal world, the fork handle could be suspended by its ends and tested to see how much weight it will hold (to simulate your figure cutting food).

Explain

Basic

- Would you recommend making fork handles out of the bioplastic you designed? What would be the advantages and disadvantages?
- What additional experiments would you like to complete if you had time?
- Why are some of the bioplastics flexible, and others brittle?
- What type of degradation would be ideal for soda bottles? (Photo-degradation so that bottles thrown by the side of the road will degrade)
- Why type of degradation would be ideal for plates and plastic utensils? (Hydro-degradation so that they would degrade quickly in the wet environment of a compost pile).

Advanced

- What types of bonding occurs in biopolymers?
- What chemical bonds are microbes able to degrade? Using the worksheet, have students compare the structure of bonds that microbes can eat.

What types of bonds are biodegradable (carbon – nitrogen, carbon – oxygen) and which are not (carbon – carbon)?

- Explain the differences in chemical bonding between flexible and brittle bioplastic? (NOTE: The plasticizer keeps the bonding from occurring between the strands. The more plasticizer that is present in the formula, the more flexible the bioplastic is.
- Design a process that would mix the chemicals needed to make plastic forks and dry them. Develop a process that could produce 100 forks an hour. Have the students make a drawing of the process and present it to the class.

Elaborate

- Develop a plastic recipe for a biodegradable plastic bag. What material properties need to be changed to make a successful bag?
- Using the Internet, find the seven types of resin identifier codes included inside the recycling symbol. What are the advantages and disadvantages of each type of plastic?
- Perform a test of degradability using the plastics produced. Compare degradability of standard plastic utensils, commercial biodegradable products and the ones designed using the biodegradation activity.

Nature of engineering (See introduction in background materials).

- Divide students into two groups. Assign one group the job of developing an argument that engineering designs have one right answer.
- Assign the other group the role of developing an argument that engineering problems have multiple solutions that can solve the problem equally well.
- Give the students time to find evidence to support their position.
- Ask the groups to pair up with a member of the other group and each describe their position.
- Then give the larger groups time to hone their arguments based on the discussion.
- Ask the groups to debate their assigned position with the other group. Use the ensuing discussion to point out that engineering solutions can have multiple solutions to the problem. Point out that different types of cell phones solve the problem of personal communication and still sell products to customers. Each of the types of cell phones must meet the needs of a group of customers.

- Use this understanding to help the students see that goals of engineering are often different than science. One of the goals of science is to come up with the best explanation of a natural phenomenon. The ideal end result is an explanation that is agreed upon by a majority of scientists. In engineering, common goal is to design a product that meets the needs of a customer. It is possible to meet these needs in very different ways. For example, both roller blades and a skateboard meet the need of travelling on a sidewalk. Each design meets the need in a different way and may appeal to a different customer.
- Help the students identify the criteria and constraints for this project.
- Ask students to propose ways to meet the criteria while staying within constraints with different materials than the bioplastic created for this lesson.

Resources

Additional Resources:

- EcNow Tech
- Green Plastics Reference
- Green Plastics News

Resources Used:

- University of Hawai'i
- Types of Biodegradable Plastics
- Green Plastics
- Green Plastics: The Difference Between Plastics
- Green Plastics: Biodegradation