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ISSUES AND TRENDS

What is engineering? Elaborating the nature of engineering for K - 12 education

Jacob Pleasants[1] | Joanne K. Olson[2]

[1]Iowa State University, Ames, Iowa

[2]Texas A&M University, College Station, Texas

Correspondence Jacob Pleasants, 1140 Biorenewables Research Laboratory, Iowa State University, Ames 50010, IA. Email: jbpleasa@iastate.edu

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the NOE construct. This paper presents the NOE via a framework synthesized from studies of the engineering discipline from philosophical, historical, and sociological perspectives, as well as perspectives from within the engineering field. The framework identifies and elaborates nine features of engineering, each of which capture an important aspect of the NOE. For teachers, these features serve as points of entry for discussing NOE ideas with students. For researchers, the features provide a set of constructs to guide future inquiries into teachers' and students' NOE knowledge.

KEYWORDS nature of engineering, nature of science

1 | INTRODUCTION

As the *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013) continue to be adopted in the United States, engineering is increasingly becoming part of science education efforts. Even among states that have not adopted the NGSS, many have developed their own engineering education standards (Moore, Tank, Glancy, & Kersten, 2015). The introduction of this content area into K - 12 education presents many challenges for teachers, who are unlikely to have had coursework in engineering (Banilower et al., 2013) and often possess misconceptions

about the engineering discipline (Cunningham, Lachapelle, & Lindgren - Streicher, 2006; High et al., 2009). Teachers' misconceptions about the nature of science (NOS) are well documented (e.g., Lederman & Lederman, 2014), and McComas and Nouri (2016) express concerns that placing engineering in the science curriculum is likely to cause these disciplines to be conflated, despite the very different ontological and epistemological assumptions underlying them. To avoid conflation of science and engineering, teachers and students must understand the structure of the engineering discipline, including how it is related to science.

Many have called for K - 12 students to gain a better understanding of the structure of the engineering discipline (International Technology Education Association [ITEA], 2007; Lachapelle & Cunningham, 2014; Moore et al., 2014; National Academy of Engineering [NAE], 2008, 2010; National Research Council [NRC], 2014; National Academy of Engineering and National Research Council [NAE & NRC], 2009). Just as science learning is enhanced by accurately teaching the NOS (Clough, 2006), learning engineering should include accurate instruction about the ***nature of engineering*** (NOE), particularly when science and engineering are taught together within the context of the science curriculum. The NOS "is often used in referring to issues such as which science is, how it works, the epistemological and ontological foundations of science, how scientists operate as a social group and how society itself both influences and reacts to scientific endeavors" (Clough, 2006, p. 463). We conceptualize the NOE as analogous to the NOS in that it includes issues relevant to the structure of the engineering discipline: what engineering is, how it works, how engineers conduct their work, the relationship between engineering and other fields of study such as

science, and how engineering influences and is influenced by society.

Although the NOE has been identified as a learning goal for K - 12 engineering education, it has generally not

been given priority within K - 12 engineering education efforts, which tend to focus primarily on teaching students the practices needed to engage in engineering design (Brophy, Klein, Portsmore, & Rogers, 2008; Crismond & Adams, 2012; Dym, 1999; NAE & NRC, 2009). Many state engineering standards include concise definitions of engineering and engineering design, and some discuss certain fields of engineering, but the NOE does not figure prominently in them (Carr, Bennett, & Strobel, 2012). The NGSS, for instance, describe engineering almost exclusively in terms of design practices (Cunningham & Carlsen, 2014). Engineering practices are important, but learning the practices of a discipline does not necessarily lead to understanding the nature of that discipline (Bell, Mulvey, & Maeng, 2012; Lederman & Lederman, 2014; Sadler, Burgin, McKinney, & Ponjuan, 2010). The NOE must therefore be regarded as its own distinct learning goal, one that demands greater attention within K - 12 engineering education.

Although engineering practices garner the most attention in both the NGSS and research on engineering education efforts in K - 12 science education, a growing research base exists related to the NOE. Studies have investigated teachers' and students' views on various NOE issues, and they have often found evidence of misconceptions. For instance, many teachers and students erroneously regard engineers as skilled laborers, such as construction workers or auto mechanics (Capobianco, Diefes - Dux, Mena, & Weller, 2011; Chou & Chen, 2017; Cunningham et al., 2006; Fralick, Kearn, Thompson, & Lyons, 2009; High et al., 2009; Montfort, Brown, & Whritenour, 2013), and many teachers and students cannot adequately differentiate science and engineering (Antink - Meyer & Meyer, 2016; Karatas, Micklos, & Bodner, 2011).

The above studies all relate to the NOE, but a common set of constructs does not yet exist to link them together. The "nature of engineering" nomenclature has not yet gained currency, and important terms used by different studies do not always align. Studies often discuss students' "perceptions" and "conceptions" of engineers and engineering (e.g., Capobianco et al., 2011; Chou & Chen, 2017; Fralick et al., 2009; Hong, Purzer, & Cardella, 2011; Johnson, Ozogul, DiDonato, & Reisslein, 2013; Weber, Duncan, Dyehouse, Strobel, & Diefes - Dux, 2011; Yaşar, Baker, Robinson - Kurpius, Krause, & Roberts, 2006), but these terms have myriad meanings. Perceptions can refer to the stereotypes students hold about engineers, students' ideas about what sorts of work engineers do, or

whether students think engineering is valuable to society. Moreover, many studies that assess "perceptions" or "conceptions" of engineers also assess participants' interest and self - efficacy in engineering, often using the same

instrument for both (e.g., Hammack, Ivey, Utley, & High, 2015; Johnson et al., 2013; Yasar et al., 2006). This

situation creates the potential for the conflation of NOE knowledge with attitudes toward engineering. A similar conflation caused significant confusion in the related field of NOS research (Lederman & Lederman, 2014), and care should be taken not to repeat those mistakes for the case of engineering.

The present work seeks to provide clarity in relation to the NOE. First, prior efforts to describe the NOE in engineering education literature are discussed, with attention to current shortcomings. Given the parallels between the NOE and the NOS, efforts to define the NOS construct are examined, and lessons are drawn from the ongoing work in that area. Informed by this prior work, the ultimate purpose of this paper is to provide a detailed framework for the NOE construct that can be used to support students' learning while also providing proving utility for researchers investigating teachers' and students' NOE views. One goal of this framework is to sharpen terminology by identifying a set of NOE dimensions appropriate and useful for K - 12 education. Another goal is to elaborate those dimensions at a level of depth and complexity that goes beyond what is currently present in the literature. For instance, documents such as the NGSS make clear that engineering is about design, but at a deeper level, what does it mean for an engineer to design a technology? How does engineering design differ from, say, architectural design or artistic design? The framework presented here brings questions such as these questions to the fore.

2 | DESCRIPTIONS OF THE NOE IN EDUCATION LITERATURE

At the K - 12 level, a collection of studies have been conducted to explore students' perceptions/conceptions of engineers and engineering (Capobianco et al., 2011; Chou & Chen, 2017; Cunningham, Lachapelle, & Lindgren - Streicher, 2005; Fralick et al., 2009; Hammack et al., 2015; Hong, Purzer, & Cardella, 2011; Johnson et al., 2013; NAE, 2008; Oware, Capobianco, & Diefes - Dux, 2007; Thompson & Lyons, 2008; Weber et al., 2011; Yasar et al., 2006). Together, these studies raise concerns over how students currently understand the engineering discipline. For instance, in their 2008 report, *Changing the Conversation*, the NAE concluded that most students "have a limited sense of what engineers actually do" (p. 7). Fralick et al. (2009) similarly concluded that "Students have inaccurate perceptions of engineering" and that this state of affairs "is probably a factor in students choosing not to pursue engineering as a career choice" (p. 67). The most common student misconceptions noted by these studies is that students tend to regard engineers primarily as manual laborers (e.g., car mechanics and construction workers).

While the studies of students' conceptions of engineering are informative, what is absent from most is a clear and detailed sense of what students ought to understand about the engineering discipline. Studies generally agree that students should view engineers as designers of technology rather than users, builders, or fixers of technology (e.g., Cunningham et al., 2005; Fralick et al., 2009; Oware et al., 2007; Thompson & Lyons, 2008; Weber et al., 2011), but beyond this distinction, descriptions of the NOE tend to be vague and terse. For instance, Capobianco et al. (2011) recommend that curricula be developed that help elementary students better understand "key qualities that transcend multiple fields of engineering," including: "An engineer is someone who is creative, uses science, uses mathematics, uses technology, works in teams, designs everything around us" and "solves problems to help people" (p. 321). These ideas are sufficiently vague that they could easily apply to many nonengineering disciplines. Notably, the characteristics they present were not based on studies of the engineering discipline, but rather were messages that they hope might "build interest, confidence, and participation in engineering" among students (p. 321).

Chou and Chen (2017) provide a similarly vague, although slightly different, definition of the "nature of engineers" (p. 477). Citing previously offered definitions of engineers (e.g., NAE, 2008), Chou and Chen state:

> *the nature of engineers is to design and develop new solutions that meet people's needs on a daily basis by using scientific principles and technological tools. In other words, the role of engineers tends to extend to research and development of new products, with a focus on the maintenance of engineering equipment. (p. 477)*

This description gives the reader little sense of what kinds "solutions" engineers produce or how they are involved with research and development. The most specific part of the description is the curious attention to the "maintenance of engineering equipment," which is rarely cited as a core part of the discipline. Taking a different approach, in an international study of secondary students' conceptions of the engineering profession, Kőycű and de Vries (2016) identify four key dimensions of engineering: "research," "development," "managerial," and "economic and social" (p. 248). They indicate that an accurate understanding of the NOE should include attention to each dimension, but they do not elaborate upon any of them.

A more extensive discussion of the NOE can be found in the *Framework for K - 12 Science Education* (NRC, 2012) within the discussion of "Core and component ideas in engineering, technology, and the application of science" (p. 203). This includes descriptions of how engineers must consider criteria and constraints during design, the process engineers use during design, how engineers use models during design, and the importance of optimization in engineering. While these descriptions provide some sense of the NOE, they do not adequately address the breadth and complexity of the construct. The *Framework* focuses primarily on describing the practices that engineers use to engage in design (Cunningham & Carlsen, 2014) to the exclusion of other important issues; for instance, the *Framework* identifies a mutually supportive relationship between engineering and science, but fails to address how the disciplines differ. In addition, some of the claims about the engineering discipline put forth in the *Framework* are not well - supported. For instance, the *Framework* explains that "the aim of engineering is not simply to design a solution to a problem but to design the best solution" (p. 209), but several scholars have argued that engineers pursue not the "optimally best" solution but rather a "satisfactory" one (Simon, 1996; Vincenti, 1990). Other researchers have similarly noted shortcomings in how engineering is described within the *Framework* and NGSS (e.g., Cunningham & Carlsen, 2014; Cunningham & Kelly, 2017; Olson, 2013).

Another more detailed description of the NOE can be found in Brophy et al. (2008). They point out that broad statements about engineering, such as that engineers apply math and science or that they solve problems, are too general and vague to be useful (a concern also raised by Davis, 1996 and Pawley, 2009). They argue that "a more clear definition of engineering [is needed] to identify what is unique about it relative to other technical domains" and they put forth a "sketch of some key cognitive components of engineering" (p. 371). They indicate that engineers engage in design and analysis of technological devices, processes, and systems, and that the technical problems they address tend to be highly complex and ill - structured. Engineers therefore require extensive content knowledge and analytical skills to engage with those problems. Their description of the engineering discipline is helpful, and more detailed than most, but still operates at a high level of generality. They also cite only Jonassen (2000) and Zuga (2004) in their discussion, leaving the reader accept their descriptions on faith. Thus, while Brophy and colleagues make clear the need for a more detailed view of the NOE, they do not make an extensive attempt to provide one.

A recent study by Cunningham and Kelly (2017) also provides a detailed view of several NOE ideas. Their work addresses the NOE indirectly, as their primary objective was to elaborate a set of "epistemic practices of engineering" (p. 492) with which K - 12 students ought to engage during engineering instruction. While this goal is separate from the goal of promoting student understanding of the NOE (Bell et al., 2012; Lederman & Lederman, 2014; Sadler et al., 2010), Cunningham and Kelly drew from studies related to the NOE to establish their list of practices. To construct their list, they built "a more robust understanding of engineering and how it works, [turning] to studies of professional engineering in practice and empirical studies of engineering in educational settings" (p. 490). In their resulting list, Cunningham and Kelly (2017) provide more in - depth descriptions of the engineering discipline than is found in other studies. An example appears in their discussion of the engineering practice of teamwork:

> *Effective communication occurs in social contexts as engineers work together in teams. These teams often include other engineers, but also clients, technicians, artists, or even politicians. Studies of engineering in practice note the importance of collaboration and the need to bring together expertise across types of knowledge. (Anderson et al., 2010; Bucciarelli, 1994; Jonassen et al., 2005; Vincenti, 1990) (p. 494)*

Not only does this section provide details of how teamwork plays out in the context of engineering work, the cited works are also studies of engineers, rather than engineering curricula or standards. Yet while Cunningham and Kelly give useful descriptions such as these, their focus was on providing evidence for their list of practices, not on comprehensively describing the NOE. As a result, many important avenues are left unexplored; for instance, Cunningham and Kelly describe several practices that engineers use to engage with engineering problems, yet they do not discuss the more fundamental question of what makes a problem an *engineering* problem. They also state that engineers engage in the practice of utilizing scientific knowledge, and that engineering is not merely applied science, but they do not describe the complex interactions between science and engineering. These observations are not intended as criticism, but to draw attention to how their focus on practices affected their discussions of the engineering discipline, and to highlight the work that remains to be done to more thoroughly elaborate the NOE. A more direct attempt to formulate a description of the NOE based on studies of engineering was taken by Karatas et al. (2011), and they are among the few scholars to employ the "nature of engineering" term. They list the following characteristics:

> *Engineering solutions are tentative (Koen 2003); involve designing artifacts and systems (Bucciarelli 2003; Dym et al. 2005; Lewin 1983; Vincenti 1990; Wulf 2002); depend on existing scientific mathematical theories as well as failures and successes in the field (Adams 2004); are affected by cultural norms and the needs of society (Adams 2004; Dym 1999; Dym et al., 2005); involve stepwise iterative and collaborative problem - solving activities (Bucciarell 2003; Dym 1994; Koen 2003 ; Vincenti 1990); require creativity, imagination, and the ability to integrate different scientific, mathematical and social values and theories in novel ways (Adams 2004; Rogers 1983); are the result of a complex human endeavor that requires analytical thinking to make complex problems simpler (Dym et al. 2005; Koen 2003; Matthews 1998); and are an holistic, open - system approach that requires considering all aspects and perspectives of not only artifacts and customers, but also its effects on the environment, individuals and society, and culture. (Adams 2004; Mitcham 1998; Rophl 2002) (p. 125)*

This list of statements was also utilized in a later study by Karatas, Bodner, and Unal (2016). Several aspects of this list are noteworthy. First, many of the sources cited here are the same as those used by Cunningham and Kelly (2017), but Karatas, Micklos, and Bodner do not indicate how or why they selected the 13 texts they cited. Second, and more important, several of the declarative statements on this list do not provide enough detail to give an informed view of the NOE. In what sense, for instance, are "engineering solutions" "tentative?" If an engineering design is used to create a physical artifact (e.g., a bridge), is that design still tentative? Engineering solutions might be impacted by “cultural norms and the needs of society,” but how and to what extent? “Social values” are mentioned, but this raises many questions about the complex values that underlie engineering, including profit or political motives.

In contrast to the K - 12 - oriented works discussed so far, a significant number of studies focused on college - level engineering education seek to better understand the work of practicing engineers (e.g., Davis, 1996; Holt, 1994; Holt & Radcliffe, 1992; Jonassen, Strobel, & Lee, 2006; Sheppard, Colby, Macatangay, & Sullivan, 2007; Solomon & Holt, 1993; Trevelyan, 2007). Many of these studies primarily focus on the perspectives and practices of practicing engineers to draw conclusions about the discipline. The motivation behind such studies is the goal of improving college - level engineering education: if engineering educators better understand what engineers do in the workplace, then they can presumably better prepare students for their future careers (Holt & Radcliffe, 1992; Jonassen, Strobel, & Lee, 2006; Pawley, 2009). This approach is well represented by the much - cited work of Dym,

Agogino, Eris, Frey, and Leifer (2005), who summarize a wide variety of research on the NOE design thinking, as well as research on teaching and learning engineering design, to put forth recommendations for college - level

engineering design education.

Studies of practicing engineers can and should inform the NOE construct for K - 12 students; syntheses of those studies, such as the work of Dym et al. (2005), are especially useful in this regard. However, the college - focused studies of the engineering discipline do not offer sufficient guidance for K - 12 educators seeking to help their students better understand the NOE. The primary concern for those studies is to better inform college engineering education programs, which have a significantly different focus than K - 12 engineering education efforts: college programs seek to prepare their graduates for the engineering workplace, but most K - 12 students will not become professional engineers. Moreover, studies focused on improving college - level engineering programs do not generally discuss what *students* ought to know about the NOE.

In summary, direct discussions of the NOE construct are sorely lacking within the field of K - 12 engineering education. As noted above, many studies have identified student misunderstandings of the engineering discipline while not offering a clear or detailed description of what an accurate understanding entails. Some studies do provide more extended descriptions of the engineering discipline, and together they give a sense of the breadth of ideas that comprise the NOE. However, some of the ideas that have been put forth are problematic, as discussed above. In general, the issue is that the NOE construct has not been the focus of discussion or debate within the literature. This is in sharp contrast to NOS research, where many ongoing and lively debates occur over how to describe the NOS construct for the purposes of K - 12 education (cf. Irzik & Nola, 2011; Lederman & Lederman, 2014; M. R. Matthews, 2012). If student understanding of the NOE is indeed a goal for K - 12 engineering education

efforts, then much more attention must be given to the NOE construct. Given the parallels between the NOS and NOE, we argue that advances within the NOS research community can do much to inform the development of a

robust NOE framework.

3 | GUIDANCE FROM THE NOS

Compared to NOS research, inquiries into the NOE for K - 12 education are in their infancy. Lessons learned from years of NOS scholarship can therefore be informative for developing the NOE construct. NOS is a hybrid construct that aims for a description of what science is, how science works, and what scientists are like (Lederman & Lederman, 2014; M. R. Matthews, 2012; McComas, Clough, & Almazroa, 1998; McComas & Olson, 1998). NOS scholarship is marked by active and lively debates, but consensus can be found on two important points. First, scholars agree that the NOS construct ought to be substantially informed by the history, philosophy, and sociology of science, as well as views from practicing scientists (Abd - El - Khalick, 2014; Hodson & Wong, 2014; M. R. Matthews, 1992, 1994; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003; Smith, Lederman, Bell, McComas, & Clough, 1997). Second, the NOS research community agrees that the NOS construct should address ideas about the science discipline that are important for K - 12 students to understand. Many disagreements exist over *which* ideas about the discipline are most crucial for K - 12 students, but the K - 12 focus of the NOS construct is not in dispute (Lederman & Lederman, 2014; McComas et al., 1998; McComas & Olson, 1998). This means that the NOS does not provide a comprehensive account of the science discipline. For example, an exhaustive account of what scientists do would necessarily include attention to the fact that most academic scientists devote considerable time to managing laboratory equipment, advising students, and teaching courses. However, descriptions of these activities do not appear on any lists of NOS ideas as they offer little insight into the fundamental aspects of what science is or how it works.

A complete discussion of the ongoing debates among NOS scholars is beyond the scope of this paper, but a controversial topic that is relevant for the present work is how best to represent the various dimensions of the NOS construct. Some advocate that key NOS dimensions be resolved into declarative statements, sometimes referred to as “tenets,” that put forth what they argue to be well - supported views about science (e.g., Abd - El - Khalick, 2014; Lederman & Lederman, 2014). Those who advocate for such lists often argue that they provide educators with useful touchstones on what can otherwise be dauntingly complex topics. However, tenet lists have been criticized on the basis that they obscure essential complexities and nuances within many NOS issues by

making sweeping generalizations that distort the NOS (cf. Allchin, 2011; Clough, 2007; Eflin, Glennan, & Reisch, 1999; Hodson & Wong, 2014; Irzik & Nola, 2011; M. R. Matthews, 2012).

An alternative approach to "tenets" proposed by M. R. Matthews (2012) is to outline a collection of "features of science (FOS) to be elaborated, discussed and inquired about, rather than nature of science (NOS) items to somehow be learnt and assessed" (p. 15). For example, instead of stating that "scientific knowledge is tentative (subject to change)" (Lederman & Lederman, 2014, p. 601), M. R. Matthews (2012) suggests that a feature of science to investigate is its "tentativeness" (p. 15). That is, rather than indicate that scientific knowledge *is* tentative, one can ask questions about the *extent* that it is tentative, and what it *means* for it to be tentative. Eflin et al. (1999) argue for a similar approach and recommend a "taxonomy of philosophic issues" (p. 112) as a starting point for NOS education, and Clough (2007) also argues that NOS issue be framed as questions rather than tenets to stimulate student discussion of NOS ideas.

4 | METHOD OF DEVELOPING FEATURES OF ENGINEERING

4.1 | General considerations for the NOE construct

Our approach to formulating the NOE construct is modeled on the more well - established NOS construct in several

respects. First, noting the consensus regarding the fields of scholarship that inform the NOS construct, we anchor our formulation of the NOE in studies of the engineering discipline by philosophers, historians, sociologists, and practicing

engineers. Consensus also exists that the NOS addresses what K - 12 students should understand about what science is and how it works; we therefore conceptualize the NOE as referring to what K - 12 students ought to understand about the engineering discipline. Along these lines, just as the NOS does not focus on the advising or teaching responsibilities of academic scientists, our formulation of the NOE does not focus on activities such as supervising contractors, procuring parts from vendors, or making sales to potential customers. While some or even most engineers might engage in these activities as part of their work, they are not distinctive features of the discipline, and teaching students about them would likely do little to elucidate the NOE. We do not argue that comprehensive descriptions of engineering have no value. Trevelyan (2007), for instance, provides a description of many of the "less glamorous tasks that designs also have to accomplish" (p. 192), and such descriptions can certainly inform collegiate engineering education programs. However, they lie outside of our focus on developing a construct for K - 12 education.

Finally, drawing from the ongoing debates over the value of NOS "tenets," the NOE framework we present in this paper follows the overall approach of M. R. Matthews (2012). We present a set of "disciplinary features of engineering" that highlight areas of interest for K - 12 engineering education rather than a set of declarative statements. Within each of those features, we also identify key questions to be "discussed and inquired about" (M. R. Matthews, 2012, p. 15), which also is in line with suggestions made by Clough (2007). Engineering, like science, is a complex endeavor, and taking this approach provides an opportunity to elaborate upon each of the features while also acknowledging their many nuances. In addition, the approach acknowledges that while consensus might exist around which disciplinary features are important, many issues are still debated for each of those features.

Although our approach to conceptualizing the NOE is similar to approaches used to conceptualize the NOS, the ideas comprising the constructs differ substantially. Even though science and engineering are related, they are distinct disciplines each with their own defining features. Whether stated as tenets or features, the dimensions of the NOS are necessarily different from those of the NOE, just as would be the case for any distinct discipline.

4.2 | Identifying sources to inform the NOE construct

As noted above, developing a set of disciplinary features of engineering requires examining the scholarship of those who have taken the discipline of engineering as an object of study. A significant challenge, however, lies in the breadth of scholarship on engineering; a comprehensive review of the literature in this domain is impractical. The

more modest objective pursued in the present work was to review *representative* works from the disciplines in which we chose to anchor our formulation of the NOE: philosophy, history, and sociology of engineering, as well as perspectives from within the engineering field. Key features of engineering could then be determined by identifying themes that cut across these varied perspectives.

In the first phase of our process, we gathered relevant works in three different ways. First, we identified relevant texts that were obtained during a recent extensive review of the nature of technology literature conducted by the authors (Pleasants, Clough, & Olson, 2018). Although engineering has not been given extensive attention within the philosophy and history of technology (Michelfelder, McCarthy, & Goldberg, 2013), a major theme that was identified during our prior review was the process of technological development. Because engineering plays a significant role in that process, many of the perspectives on that theme address engineering (e.g., Bijker, Hughes, Pinch, & Douglas, 1987;

TABLE 1 Texts reviewed during initial phase of search

Title of text (year of publication) Authors/editors Disciplinary perspective

Designing Engineers (1994) Bucciarelli Sociology

The Origins of the Turbojet Revolution (1980) Constant History

ed.) (2012)
ineering

Engineering Design Methods: Strategies for Product Design (3rd ed.) (2000)

s Engineering

Engineering Design: Representation and Reasoning (2nd

The Civilized Engineer (1987) Florman Engineering

Human - Built World: How to Think About Technology and Culture (2004)

es History

cience in Action: How to Follow Scientists and Engineers Through Society (1987)

Technical Artefacts: Creations of Mind and Matter: A Philosophy of Engineering Design (2012)

Case Studies in Engineering Design (1998) C. Matthews Engineering

Thinking Through Technology: The Path Between Engineering and Philosophy (1994)

am Philosophy

vention by Design: How Engineers Get from Thought to Thing (1996)

The Design of Everyday Things: Revised and Expanded Edition (2013)

The Sciences of the Artificial (3rd ed.) (1996) Simon Philosophy

What Engineers Know and How They Know It (1990) Vincenti History

Edited volumes *The Social Construction of Technological Systems* (1987) Bijke

Philosophy
Philosophy

Douglas (Eds.)

Philosophy, history, sociology

Liberal Education for 21st Century Engineering: Responses to ABET/EC 2000 Criteria (2004)

Philosophy of Technology and Engineering Sciences (2009)

rs (Ed.) Philosophy, history

Engineering
Engineering

Philosophy and Engineering: Reflections on Practice, Principles, & Process (2013)

hilosophy and Design: From Engineering to

elfelder, McCarthy, and

Kroes, 2009, 2012; Meijers, 2009; Mitcham, 1994; Norman, 2013; Petroski, 1996), and as such those texts were used for the present work. Second, we obtained works cited by previous researchers to describe the engineering discipline (e.g., Cunningham & Kelly, 2017; Karatas et al., 2011). This step was not intended to replicate prior efforts, but to ensure that important works were not omitted. Third, we searched the library of the first author's university for edited volumes that addressed philosophy of engineering. Edited volumes were considered particularly valuable as they present perspectives on a variety of themes from multiple authors, and are therefore particularly useful for pointing toward additional relevant texts. The full set of texts obtained from these three approaches is listed in Table 1.

After reviewing the works in Table 1, the second phase of the process identified additional texts by following the citation trails within the reviewed texts. This "snowball" method has shortcomings in that it does not necessarily achieve a review of extensive breadth. However, the broad net that was cast during the initial gathering of texts for the review meant that each of the targeted disciplinary perspectives (philosophy, history, sociology, and engineering) were well represented, as indicated in Table 1. The full list of texts that were included in both phases of the review are noted with an asterisk (*) in the references list.

4.3 | Analysis of reviewed works

Our analysis of the selected texts followed an inductive qualitative analysis approach (Merriam & Tisdell, 2015).

The goal of our analysis was to identify major areas of inquiry related to the engineering discipline, and to identify the various perspectives in each of those areas. Some of the reviewed texts also discussed topics more distantly related to engineering, such as interactions between technology and society. Unless engineering figured prominently in such discussions, they were considered not to be relevant for the review. Early in the review process, we developed a list of tentative dimensions that represented common areas of interest across the texts reviewed thus far. As additional texts were reviewed, we followed a constant - comparative approach (Glaser, 1965) to iteratively refine the list of dimensions. The refinement of dimensions continued until all of the texts in Table 1 were reviewed. Then, as we began following the citation trails within those texts (the second phase of our literature search), we used those additional texts to continue to test and refine our themes. We continued following citation trails until our set of dimensions reached stability, at which point we concluded our review.

The most significant decisions during the review process regarded how to group the different themes that we identified in the literature, many of which overlapped significantly. For example, many texts discussed various models of the engineering design process, while others analyzed the characteristics of engineering design more generally. Several considerations guided our decisions to either keep overlapping themes such as these distinct or combine them into a single dimension. We wanted each dimension to represent an area of significant interest within the NOE scholarship, which led us to combine overlapping themes that, individually, were less frequently discussed within the literature. However, we also wished to separate dimensions that represented distinct lines of inquiry within the reviewed texts, even if those dimensions had conceptual connections. Using the example above, we decided to keep "models of design processes" as its own dimension because a considerable quantity of scholarship discusses models of the process without analyzing the fundamental nature of design; similarly, many analyses of design in engineering do not explore specific models of the design process. A final consideration was that we sought to develop a modest number of dimensions from our review. This choice was made to keep our list of dimensions useful for educators; although a list of 20 or more themes would likely represent the reviewed literature more completely, such a long list would be cumbersome to use in educational settings.

5 | ELABORATION OF THE NOE FRAMEWORK

The review of scholarship described above yielded nine disciplinary features of engineering, each of which identifies an important dimension of the characteristics of engineering:

1. Design in engineering **2.** Specifications, constraints, and goals **3.** Sources of engineering knowledge **4.** Knowledge production in engineering **5.** The scope of engineering **6.** Models of design processes **7.** Cultural embeddedness of engineering **8.** The internal culture of engineering **9.**

What follows are elaborations of each of these features, drawing attention to important issues and perspectives found in the literature. Because these features are meant to inform K - 12 education, each is discussed at a level of generality that raises key issues while avoiding the highly technical nature of certain perspectives. For a more detailed view, the reader is encouraged to consult the texts used during the review, particularly those listed in Table 1.

Notably, most of the NOE features are most closely related to engineering design. A potential criticism of this emphasis on design is that many professional engineers engage in activities that are not directly design - related (Trevelyan, 2007). While that might be the case, our set of dimensions ultimately reflects the areas of emphasis within the literature, which have generally been on engineering design. In fact, many have argued that design is the fundamental aspect of engineering (Crismond & Adams, 2012; Dym et al., 2005; Dym & Brown, 2012; Kroes, Light, Moore, & Vermaas, 2008; Simon, 1996). Furthermore, the NOE construct is intended for use within K - 12 educational settings, in which design has been given considerable attention (Brophy et al., 2008; Dym, 1999; NAE & NRC, 2009; NRC, 2012). Thus, while we acknowledge that engineering encompasses more than design, an idea which is addressed by the fifth dimension in the framework, the emphasis on design among the dimensions has considerable justification.

As M. R. Matthews (2012) indicated, features ought to be “elaborated, discussed, and inquired about” (p. 15) during instruction. To this end, many questions are posed during the elaborations of the features, and while answers to these questions are sometimes offered, they should not be regarded as definitive. The intent is that the questions and perspectives might provide a useful guide for engaging teachers and students in conversations about the NOE. In addition, the questions and elaborations that follow provide guidance for researchers interested in assessing individuals’ knowledge of the features.

5.1 | Design in engineering

Design has been argued to be a defining feature of engineering, one that separates it from disciplines such as science (Dym & Brown, 2012; Simon, 1996). Design, however, is not unique to engineering (Hughes, 2004; Kroes et al., 2008; Simon, 1996), so how does engineering employ design in a way that is specific to the discipline? Engineering design is often described as problem - solving (Dym & Brown, 2012; Jonassen et al., 2006; Sheppard et al., 2007; Simon, 1996), but this does little to illuminate the characteristics of the process that are either crucial for or unique to the discipline (Dorst & Van Overveld, 2009; Hatchuel, 2002; Pawley, 2009; Pitt, 2013).

Kroes (2012) argues that a distinguishing characteristic of engineering is its concern with the *practical* design of *technologies*. Note that many of the following discussions focus on technologies as physical objects such as hammers or cars, but technologies also include processes and systems (Koen, 2013; Mitcham, 1994; Pacey, 1983); the ideas that follow apply equally to any of the broad meanings of “technology.” While engineers might consider esthetics as part of their designs (Kroes, Franssen, & Bucciarelli, 2009; Petroski, 1996), the technologies they produce are primarily practical or functional in nature (Bucciarelli, 1994; Cross, 2000). In contrast, nonengineering designers might be primarily concerned with esthetic appeal, or marketing and sales.

How does the practical/functional focus of engineering influence how design is undertaken in engineering? Engineers must attend to both the internal workings of a technology (its technical form) and to how the technology will be used by people (its function in a social environment). The challenge for the design engineer is how to move from an idea of how a technology must function to the internal structure that will produce that desired function (Dym & Brown, 2012; Kroes, 2012; Simon, 1996). While the physical form of a technology does not completely *determine* its function (Feenberg, 2010), it must at least *permit* the desired function. How a designer manages to move from desired function to internal form remains somewhat mysterious; it cannot be achieved mechanistically or algorithmically, and requires great creativity (Cross, 2000). As designers, engineers do not physically produce technologies, but rather generate the specifications for a technology’s creation (Dym & Brown, 2012; Petroski, 1996). Because designs are handed off to others for production, they must sufficiently describe the technology for the purposes of production, and often include detailed drawings as well as textual and numerical information (Dym & Brown, 2012).

Another critical aspect of engineering design is that it typically requires the coordinated efforts of teams of engineers, each with various specializations, as well as technicians and scientists (Jonassen et al., 2006; Trevelyan & Tilli, 2007). Because technological projects involve many divisions of labor, and delegations of work to contractors and specialists, few engineers engage with more than a small component of any technological design process (Bucciarelli, 1994; Cross, 2000; C. Matthews, 1998; Vincenti, 1990). To what extent is the design of complex technologies fundamentally different than the design of relatively simple ones? Does engineering design take on a different character when it involves the coordinated efforts of large numbers of individuals? How much of engineering design is actually the *management* of diverse teams?

5.2 | Specifications, constraints, and goals

The above description of design takes for granted that engineers have a description of how a yet - to - be - designed technology must function, but how is that description generated? How do engineers determine what qualities a technology should possess? The design tasks that are posed to engineers often originate from an external source, such as the management of a technology firm or a client with whom a firm has a contract. When these tasks are presented to engineers, they are often ill - defined: they might specify a goal to be achieved or a technological problem to be resolved, but are described only generally. Engineers must translate ill - defined goals into specifications that can be used to guide design work (Bucciarelli, 1994; de Vries, 2009; Dym & Brown, 2012; Kroes, 2012; M. R. Matthews, 1994; Van de Poel, 2013; Vincenti, 1990). The process of creating detailed specifications is so crucial that Newberry (2013) argues it to be a defining characteristic of engineered technologies.

How do engineers go about this translation process? The task always takes place in a social context and can thus be highly complex. A team of engineers working on a project must negotiate how a successful design will be defined, in terms unambiguous to those involved (Bucciarelli, 1994). Vincenti (1990) presents an example of this process in his description of how airplane designers developed a set of *flying quality* characteristics. In the early 20th century, a goal for airplane design was to make them relatively easy and pleasant to fly, but this goal needed to be defined in much more concrete terms to be useful for designers. Research engineers therefore worked with test pilots to develop a set of quantitative specifications that defined the meaning of flying quality. Developing these specifications required extensive interactions and negotiations between engineers and pilots.

In addition to specifications for a successful design, engineers must also navigate various constraints on their designs. Design constraints are limitations placed on the designed technology in terms of safety, reliability, cost, or other factors (Cross, 2000; Kroes, 2012; M. R. Matthews, 1994). How do engineers determine which constraints need to be considered during design? These, too, must be socially negotiated, and are often renegotiated during the process of design. Engineers, for instance, must decide how much cost is too much, what kinds of safety tolerances must exist, and how reliable a technology must be. While these are sometimes given to engineers as quantitative specifications or regulations, more often the designers must translate vaguely stated constraints much as they

translate specifications (Bucciarelli, 1994; Van de Poel, 2013). Dym and Brown (2012), in fact, argue that constraints and specifications are essentially synonymous, and are treated by designers in the same fashion.

5.3 | Sources of engineering knowledge

Engineers utilize knowledge from science and mathematics, but consensus exists that engineering is not merely applied science, and that it has a knowledge base of its own (Houkes, 2009; Koen, 2013; Kroes, 2012; Vincenti, 1990). If this is the case, what is the nature of that knowledge base?

When engineers engage in design, they draw on their knowledge of existing technologies (Cross, 2000). Often, engineers work within a well - explored technological area, in which the "normal configuration" (Vincenti, 1990, p. 209) of a technology has been established. That is, the engineer knows to a significant extent how various technical components ought to be arranged. Dym and Brown (2012) describe this situation as "routine" engineering design. Even when design is less routine, engineers can rely on analogies to connect known and unknown technological spaces (Bulleit, 2013; Cross, 2000; Ozkan & Dogan, 2013; Petroski, 1996; Vincenti, 1990). Even when working in novel domains, designers must have a sense of what Polanyi (1958) calls the "operational principle" underlying a technology: an overall understanding of how a device or system functions.

The knowledge described above has connections to scientific knowledge, but ought to be considered a separate knowledge base. Even when engineers utilize theoretical knowledge, that knowledge often belongs to the domain of engineering rather than science (Vincenti, 1990). Unlike scientific theories, which are used to understand natural phenomena, engineering theories are used by engineers for the practical purposes of design. Theories that cannot generate information for design, usually in the form of calculable quantities, are of limited use to engineers (Houkes, 2009).

5.4 | Knowledge production in engineering

If a knowledge base unique to engineering exists, how is that knowledge developed? An important mode of engineering knowledge production, though not the only one, is engineering research, sometimes called "engineering science." This form of engineering work is most visible in universities (Adams, 2004), but also occurs in industrial research and development laboratories (Channell, 2009; Vincenti, 1990).

How is engineering science related to, but separate from, the natural sciences? Both disciplines are concerned with the production of knowledge (Houkes, 2009). The methods used by the two fields are also extremely similar, and they even have similar means of disseminating that knowledge, such as professional journals and conferences (Banse & Grunwald, 2009; Vincenti, 1990). However, the ultimate goals of the knowledge - producing activities of science and engineering science differ: for science, knowledge about natural phenomena is an end in itself, while for engineering science, the produced knowledge is only a means to be used for the purposes of designing technologies (Banse & Grunwald, 2009; Dym & Brown, 2012). While science aims toward understanding and explaining natural phenomena, engineers do not necessarily require explanation of the phenomena at hand. Rather, engineering science is content to generate models of phenomena that produce useful results, even if they offer little explanatory power (Houkes, 2009; Vincenti, 1990).

Because the goal of engineering science is on generating knowledge for use in design, engineering science generates knowledge *related to specific technologies* (Channell, 2009; Petroski, 1996; Vincenti, 1990). The products of engineering science might include knowledge of how particular technologies function, or analytical tools and models that can be applied to a range of technological phenomena (Dym & Brown, 2012).

5.5 | The scope of engineering

Some scholars of engineering argue for an expansive view of the discipline that encompasses essentially all aspects of technological work (e.g., Florman, 1987; Koen, 2003). A common definition of engineering that shares the

expansive view is that "engineers solve problems" (e.g., Sheppard et al., 2007). Many, however, argue that such views are overly permissive (e.g., Davis, 1996; Pawley, 2009). Engineers work with technology, but technological activity in general includes much that is not engineering. For instance, craftspeople typically are both the designers and producers of technologies, but modern engineers are not the ones to physically carry out the production (Cross, 2000; Dym & Brown, 2012; Kroes, 2012; Mitcham, 1994; Petroski, 1996; Trevelyan, 2007). Similarly, although engineers must consider a technology's users when designing it, engineers are not typically intended to be the primary consumers or operators of a given technology (Norman, 2013; Trevelyan & Tilli, 2007; Vincenti, 1990). Even though engineers are frequently involved with the development of new technologies, not all inventions are necessarily the product of engineering (Mitcham, 1994; Newberry, 2013)

However, the work of engineers includes more than just technological design (Holt & Radcliffe, 1992; Mitcham & Schatzberg, 2009; Trevelyan, 2007). Many engineers engage in engineering science rather than design, which is a research - focused activity, as described above (Houkes, 2009; Petroski, 1996; Vincenti, 1990). Other engineers act as overseers of projects, particularly in the case of civil engineering (Florman, 1987; Trevelyan, 2007). Instead of designing new technologies, engineers might also study existing technologies, particularly in the case of unexpected failure (C. Matthews, 1998), or engage in certain maintenance activities (Mitcham, 1994; Trevelyan & Tilli, 2007). Given this range of activity, where is the boundary of engineering practice? Can certain practices be regarded as the "core" of engineering, with others as more "peripheral?"

5.6 | Models of design processes

To what extent is there, or should there be, an overall structure to the process of design? This is the central question in the field of design methodology, the goal of which is to better understand and ultimately improve the engineering design process (EDP) (Banse & Grunwald, 2009; Kroes, 2002). Many models of the EDP, often in the form of flowcharts, have been put forth and reproduced in the literature (cf. Cross, 2000; Dym & Brown, 2012). These EDP models vary in terms of their level of generality; some include as few as three broad phases, while others specify many phases, each with multiple subphases (Dym & Brown, 2012; Pahl, Wallace, & Blessing, 2007). EDP models can either be *descriptive* by attempting to describe actual design practices, or be *prescriptive* by providing normative suggestions for what design ought to be like (Cross, 2000; Kroes, 2002).

Many questions surround these proposed EDP models. What is a desirable degree of specificity for an EDP model? Those that are too vague are not much use to those wanting to learn how to design (Dym & Brown, 2012), but adding too much detail can "obscure the general structure of the design process by swamping it in the fine detail" (Cross, 2000, p. 36). How do descriptive and prescriptive models of the EDP differ? Cross (2000) notes that many prescriptive EDP models place great emphasis on initial analysis and problem definition, yet examinations of expert designs typically reveal that they start generating potential solutions very early in the process (Dorst & Cross, 2001). While some models attempt to take this into account (e.g., March, 1984), many do not. Finally, there is the question of whether a generic EDP model is appropriate, given the breadth of engineering design work. Dym and Brown (2012) caution against regarding any model as the "The" design process, and others question whether any EDP model can adequately capture the complex and context - dependent process of design (cf. Bucciarelli, 1994; Dorst & van Overveld, 2009; Houkes, 2008; Kroes, 2012; Mitcham, 1994).

Why do engineers seem to be so interested in generating EDP models, especially those in the form of flowcharts? This is not, for instance, something that is often seen within studies of science methodology (Kroes, 2002). One potential explanation is that a great deal of pressure is placed on design engineers to work quickly, with minimal costs, and with few errors; such efficiency pressures are far less apparent in science

(Bucciarelli, 1994; Cross, 2000; Vincenti, 1990). These pressures call attention to the design process itself, and how to potentially improve it, which leads naturally to formal prescriptive models. EDP flowcharts can be useful when coordinating the efforts of large teams of engineers, which often occurs during the design of complex technological devices (e.g., airplanes) and systems (Cross, 2000; Kroes, 2012). They are also useful pedagogical tools for novice designers

(Dorst & van Overveld, 2009). Dorst and Cross (2001) argue that EDP models are best regarded as tools for beginning designers, rather than descriptions of expert practice.

5.7 | Cultural embeddedness of engineering

Karatas et al. (2011) state that engineering designs "are affected by cultural norms and the needs of society" (p. 125). While this statement conveys something important about engineering, the more important questions are *how* culture influences design, and *how* engineering design interfaces with society. Areas of interest include the ways that society provides inputs for engineering design, and the ways in which the outputs of design interact with society.

Although engineers are concerned with the technical details of technological systems, nonengineers can still substantially influence those systems (Constant, 1980; Vincenti, 1990). For instance, social groups strongly influence which problems a technology is meant to address, the values underlying the design of a technology, and what a given technology is "for" (Franssen, 2008; Van de Poel, 2013). Such issues are negotiated by many stakeholders, including the industrial organizations in which the technology is being developed, the intended users of the technology, and the designers of the technology (Bucciarelli, 1994; Idhe, 2008; Latour, 1987; Pinch & Bijker, 1987). The industrial firms that support design work are particularly crucial, as they provide the resources for

design activities. Firms are situated in larger social, economic, and political contexts, all of which influence the work of engineers in those firms (Bucciarelli, 1994; Van de Poel, 2013).

Society influences engineering work, but engineers also affect society through the technologies they develop. An important area of debate is how much responsibility engineers should assume for the effects of the technologies on which they work. Engineers are responsible for making sure that they conduct their work in accordance with professional standards and norms; because technological failure can cause considerable harm, engineers have ethical responsibilities to do their work competently (Florman, 1987; Robison, 2013). Engineers also must consider to some extent how technologies will interface with end - users (Houkes, 2008; Kroes et al., 2008; Norman, 2013; Vincenti, 1990). Many, however, argue that engineers must take on more responsibility for the myriad ways that their technological products affect society (Feng & Feenberg, 2008; Latour, 1992; Mitcham, 1994; Van de Poel & Kroes, 2014; Van Gorp & Van de Poel, 2008). Even though the ways that technologies affect society are difficult to predict, engineers must nevertheless consider potential consequences (Verbeek, 2008).

5.8 | The internal culture of engineering

Engineering takes place within a broader social context, but what are some of the cultural features of engineering itself? Some suggest that there are characteristically "engineering" ways of thinking and engaging with problems in the world (e.g., Florman, 1987, 1996), although not all agree with this notion (e.g., Pitt, 2013). This might include characteristics of engineers such as perseverance and attention to detail, or the sorts of values that tend to underlie engineering work (Van de Poel, 2013). It might also include typical problem - solving approaches used by engineers, and one that has received considerable attention is the use of reductionism (Adams, 2004; Bucciarelli, 1994; Cross, 2000; Hughes, 2004; Kroes et al., 2008; C. Matthews, 1998; Vincenti, 1990). Subdividing and reducing real - world situations to entities such as force or voltage is what allows engineers to draw upon abstract mathematical models or physical principles, which have considerable advantages (Petroski, 1996; Pitt, 2013; Simon, 1996). On the other hand, technologies do not exist only as abstractions, and an overreliance on reductionism can cause inattention to important real - world complexities, such as user experiences (Bucciarelli, 1994; Norman, 2013). Another more visible aspect of engineering culture is the high proportion of men in engineering, who make up 85% of the profession (National Science Foundation [NSF], 2017). The effects of this gender imbalance on workplace interactions have been well documented (Faulkner, 2009; Hatmaker, 2013). Similarly, certain minority groups are underrepresented within the engineering discipline, at least within the United States. For example, only

4.3% of engineers are African American, although they make up 12.4% of the US population (NSF, 2017). In what ways do issues of underrepresentation affect the ways that engineers work, the technologies that engineers design, or the research work of engineers? The lack of representation within certain industries can potentially result in biased technologies (e.g., Wachter - Boettcher, 2017), but these questions are only beginning to be explored.

In describing the culture of engineering, an important complexity is that many specializations exist within engineering, each of which have their own subcultures. Through their educational and professional experiences, engineers develop ways of representing the world in terms of abstractions and conceptual models (Dym & Brown, 2012). These representations vary between different engineering specializations; electrical engineers “see” the technological world in terms of currents and voltages, while mechanical engineers “see” technologies in terms of stresses and torques. Complex technological projects bring together engineers from a variety of backgrounds, as well as nonengineers, and these different ways of viewing the world must be continuously negotiated and resolved (Bucciarelli, 1994, 2001; Vincenti, 1990).

5.9 | Engineering and science

As is evident in several of the above features of engineering, the relationship between engineering and science is embedded in many facets of the engineering discipline. Overall, science is held in high esteem by the engineering community, as evidenced by the prominent role of science coursework during collegiate engineering education (Adams, 2004; Bucciarelli, 1994; Florman, 1987; Simon, 1996). Indeed, the association between modern engineering and science is often taken to be a distinctive feature of modern practice, separating it from the more crafts - based and artisanal approaches of the past (Florman, 1987; Petroski, 1996; Vincenti, 1990).

As preceding discussions have made clear, however, science and engineering are not identical. Scientific knowledge has utility for engineers, but is not sufficient to guide design work (Channell, 2009; Houkes, 2009; Koen, 2013; Kroes, 2012; Simon, 1996; Vincenti, 1990). Engineering science shares many characteristics with the natural sciences, but is directed toward different goals and thus uses different approaches (Banse & Grunwald, 2009; Mitcham & Schatzberg, 2009; Petroski, 1996; Vincenti, 1990). Yet scientists and engineers often find themselves working side - by - side within technological organizations (Bucciarelli, 1994). What are the different roles that scientists and engineers play in technological activity? To what extent can their work be meaningfully disentangled in technological projects?

5.9.1 | Summary of features

The nine disciplinary features of engineering discussed here make clear the nuances and complexities inherent in the NOE. Understanding the engineering discipline entails far more than being able to identify or even use practices they employ; it demands understanding the kinds of work with which engineers engage, how engineers utilize and produce knowledge, the relationships between engineering and science, and the social environment that underlies all of these issues. Understanding the NOE means gaining a sense of the complexities underlying each of the features discussed above. The features cannot be reduced to a set of declarative statements, but rather are themes with which to engage and elaborate (M. R. Matthews, 2012). While nine features were addressed here, additional important features can likely be identified. The list is not meant to be exhaustive, but rather is intended to highlight some of the most frequently discussed NOE issues. Multiple ways could be used to organize the list of disciplinary features, as they are all highly interrelated.

6 | DISCUSSION AND IMPLICATIONS

US policy documents make clear that K - 12 engineering education should include not only learning how to engage in engineering practices, but also learning *about* the engineering discipline (ITEA, 2007; NAE, 2008, 2010; NAE &

NRC, 2009; NGSS Lead States, 2013; NRC, 2014). However, these documents offer few details regarding *what* students ought to learn about the NOE; while they put forth definitions of engineering and of engineering design, they do little to indicate the complexities and nuances of the NOE. The purpose of the NOE framework presented here is to illuminate those nuances and complexities, and to point toward central issues that are worth addressing as part of K - 12 education.

The NOE framework makes clear that engineering, much like science, is a highly complex and multifaceted endeavor. Understanding the engineering discipline therefore requires a great deal more than learning a concise definition of engineering or learning about and engaging in steps of an EDP. This does not mean that K - 12 students ought to exhaustively explore every facet of the engineering discipline. However, if engineering is expected to be taught to students as described in NGSS, conveying engineering as a set of practices with little mention of engineering concepts or the nature of the discipline distorts the field and promotes misconceptions. This is particularly important given the expectation that engineering be taught to students in the context of learning science. These fields have important differences, and yet when taught together, teachers and students may easily conflate the two or perceive science as less important because it appears farther removed from solving immediate human problems.

Much discussion exists within the K - 12 engineering education community about how best to teach students the skills and practices associated with engineering design (Brophy et al., 2008; Crismond & Adams, 2012; Hynes & Swenson, 2013). Much less research, however, addresses how to teach students about the NOE (Crismond &

Adams, 2012). Many have argued that engineering design activities ought to reflect authentic practice, and thus ought to be informed by an understanding of the engineering discipline (Davis, 1996; Dym et al., 2005; Holt, 1994;

Hynes & Swenson, 2013; Jonassen et al., 2006; Trevelyan, 2007). Engaging K - 12 students in authentic engineering activities has some value in promoting students' understanding of the NOE. For example, utilizing flowchart models of the EDP in a way that portrays them as fluid rather than rigid, and also makes clear that they do not necessarily describe the process of expert designers, can help students avoid the inaccurate conclusion that design is a linear or step - by - step process (Crismond & Adams, 2012; Cross, 2000; Dym & Brown, 2012). However, just as students will not necessarily draw accurate conclusions about the NOS by doing inquiry - based laboratory experiences alone (Clough, 2006; Lederman & Lederman, 2014), students are unlikely to develop an accurate understanding of the NOE simply by doing engineering design activities, even ones that reflect authentic practice. Yet beyond advocating for more authentic design experiences, little has been put forth about how to improve students' knowledge of the NOE.

We argue that to promote students' accurate understandings of the NOE, explicit instruction is essential, just as it is for the NOS and any other cognitive outcome (Abd - El - Khalick & Lederman, 2000; Bell, Mulvey, & Maeng, 2016; Clough, 2006; Lederman & Lederman, 2014). Explicitly addressing the NOE includes drawing students' attention to NOE issues that arise during activities and engaging students in conversations about the NOE. Engineering design activities that reflect authentic practice are valuable in that they create opportunities for explicit instruction, but the activities will do little on their own if teachers do not seize those opportunities. The nine disciplinary features of engineering described here identify ideas that can and should be addressed with students during explicit NOE instruction. The questions posed within the description of each feature might also be posed to students during classroom discussions, and Table 2 provides additional questions aligned with each of the nine features that highlight key issues within each.

Our framework provides a starting point for addressing the NOE with K - 12 students, but more work is needed to determine which ideas are most appropriate for students at different grade levels and what a suitable end - point should be for K - 12 students' NOE knowledge. We emphasize that our recommendations for how to effectively teach the NOE to students and teachers are based on the results from empirical studies of teaching the learning the NOS. While translating the findings of NOS research to the NOE makes sense, future empirical work should

investigate the extent to which teaching and learning the NOE is similar to the NOS. For instance, future work might investigate the extent to which the NOE should be addressed across a continuum of experiences that are

more or less situated within broader science and engineering content (Bell et al., 2016; Clough, 2006).

Addressing the NOE with students necessitates that teachers have a sufficiently deep understanding of it. Yet most science teachers have not taken coursework in engineering (Banilower et al., 2013), and even those science teachers who have experience with engineering content might not be familiar with the NOE. Therefore, teachers also need instruction in the NOE that expands their knowledge of the engineering discipline and the work of engineers. The questions provided in Table 2 are therefore useful not only for K - 12 students, but also in teacher preparation programs and professional development efforts.

The features of engineering also have great utility for researchers seeking to study teachers' and students' NOE knowledge. As discussed above, the lack of a clear NOE construct has led to the confusing use of terms, such as "perceptions of engineering," that often carry multiple meanings. Instead of describing students' or teachers' perceptions of engineers or engineering *in general*, more clarity would be obtained by describing conceptions of a *specific feature* of engineering, such as the scope of engineering or design in engineering. The features presented here should not be taken as a definitive list, but as a useful starting point for further discussions and refinements of the NOE construct within the research community. As engineering becomes increasingly prevalent in US classrooms (Moore et al., 2015), more work in this area is sorely needed if teachers and students are to understand what the engineering discipline is and how it works.

TABLE 2 Thought - provoking questions related to each feature of engineering

Feature of engineering	Thought - provoking questions
1. Design in engineering	**1.** What does it mean for an engineer to design a technology? **2.** How is engineering design different from design in other disciplines? **3.** To what extent is engineering design problem - solving?

2. Specifications, constraints, and goals **1.** How are the specifications and constraints of an engineering project determined? To what extent can they change over time? **2.** How does the presence of constraints influence how engineers engage in design?

3. Sources of engineering knowledge **1.** How do engineers use knowledge from other disciplines, such as science? **2.** What kinds of knowledge are internal to the engineering discipline?

4. Knowledge production in engineering **1.** How do engineers produce the knowledge needed to engage in design? **2.** In what ways is engineering science different from, and similar to, natural science?

5. The scope of engineering **1.** What kinds of technological activities do engineers **not** generally do? Why is this the case?

6. Models of design processes **1.** What might be the value of creating a formal, flowchart model of engineering design? **2.** How well do models of the design process capture the real work of designers?

7. Cultural embeddedness of engineering s is engineering design influenced by the culture in which it is practiced? **2.** In what ways must engineers think their work?

8. The internal culture of engineering **1.** To what extent does there exist an "engineering culture?" What are some of the features of that culture?

9. Engineering and science **1.** How do engineering and science influence one another? **2.** In what respects are engineering and science different?

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ORCID

Jacob Pleasants http://orcid.org/0000-0002-1886-6270

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