Science & Education (2024) 33:679–697
https://doi.org/10.1007/s11191-022-00402-7

ARTICLE

Nature of Engineering

A Cognitive and Epistemic Account with Implications for Engineering Education

Miri Barak[1,2] · **Tamar Ginzburg**[1] · **Sibel Erduran**[2]

Accepted: 10 October 2022 / Published online: 9 November 2022

Abstract
Engineering education has slowly been making its way into schools with the aim of promoting engineering literacy, which is central to learning and working in a technology-oriented society. Educators and policy makers advocate the need for developing students' understanding of the nature of engineering (NOE); yet, there is an ongoing debate on the heuristics that should be applied. In this article, we review and discuss current studies on engineering education in schools and the integration of engineering into the science curriculum. We describe four aspects of engineering fields: Structures, Machines, Materials, and Data, each uniquely characterized by the technology used and the artefact produced. We discuss the application of the Family Resemblance Approach (FRA) to the characterization of NOE, focusing on the cognitive and epistemic domain. Accordingly, we describe NOE through four categories: Aims & Values, Engineering Practices, Methods & Methodological Rules, and Engineering Knowledge, which can guide teaching and learning about NOE. Building on the FRA, this paper provides a framework for a continuous discussion on NOE and the theoretical and practical relationships between science and engineering.

1 Introduction

In recent years, pre-college engineering education is gaining much attention and research interest among science and engineering educators (Cunningham et al., 2020; NASEM, 2020; Purzer et al., 2022). There is agreement among educators and policy makers about the need to promote the understanding of engineering and its impact on society in K-12 education (AE3 & ASEE, 2020; Antink-Meyer & Brown, 2019; McComas & Burgin, 2020; NGSS Lead States, 2013; Purzer et al., 2022). Engineering education is of growing importance for three main reasons: First, engineering literacy is central to living, learning, and working in a technology-driven world (Carr et al., 2012; NAGB, 2018; NGSS Lead

---

✉ Miri Barak
bmiriam@technion.ac.il

[1] Faculty of Education in Science and Technology, Technion, Israel Institute of Technology, 320003 Haifa, Israel

[2] Department of Education, University of Oxford, Oxford, UK

States, 2013; NRC 2012). Second, engineering encompasses skills such as problem solving, system thinking, and innovation capabilities, which are central to sustainable development of modern society (Barak & Yuan, 2021; NASEM, 2020; Purzer et al., 2022). Third, there is ongoing shortage of engineers, with engineering occupations listed as priority jobs (NAGB, 2018; NASEM, 2020). Yet, much debate still revolves around questions such as: *What engineering concepts and skills should be taught in schools? Which pedagogical approaches should be used? Where should engineering be incorporated in the K-12 curriculum? What qualifications are required for teaching engineering?* Such questions are still relevant and discussed among science and engineering researchers (e.g., Cunningham et al., 2020; Deniz et al., 2020; McComas & Burgin, 2020; Purzer et al., 2022).

From a historical point of view, engineering is embedded in our society since ancient times, since humans invented tools to facilitate daily life. The word “Engine” originates from the Latin word “Ingenium,” which refers to mental power or a clever invention. Derived from it is *Engine’er*, a word used in the fourteenth century, referring to a person who constructs and operates military machines (i.e., engines). Throughout history, engineering has been identified with the process of creating and developing artefacts that assist human function (Kroes, 2012; Mitcham & Schatzberg, 2009). Nevertheless, it is important to acknowledge that while the results of engineering may improve our lives, they can also harm us, as in the case of military machines or factories that pollute the environment.

In the last decade, engineering education has slowly been making its way into school classrooms, with the aim of promoting students’ understanding of engineering design and practice. With the publication of the *Next Generation Science Standards* in the United States (NGSS Lead States, 2013), interest and reference to engineering practices have augmented in the context of STEM education research (e.g., Kelly & Green, 2018). However, since engineering has been a central part of our society for many years, it is quite surprising that only in recent years schools have begun teaching this subject. The incorporation of engineering topics into school curriculum has been guided by experts from diverse disciplinary backgrounds and epistemological views, resulting in differences in pedagogical approaches (e.g., Daugherty & Carter, 2018; Purzer, et al., 2022; Violante & Vezzetti, 2017). These differences raise significant questions, such as: *Should engineering education be taught as a separate discipline or embedded in the science curriculum? Should teachers have an engineering degree? Can science teachers be trained to teach engineering? If so, how?* These questions are yet unsolved, as there is fairly limited scholarship about a more fundamental question: *“What is the nature of engineering?”* In this paper we address this key question through cognitive and epistemic underpinnings of engineering as a broad domain as well as the particular characteristics of various sub-disciplines of engineering.

2 Literature Background

In this section, we review and discuss current studies on engineering education in schools and the integration of engineering into the science curriculum. We present the connections and differences between engineering, science and technology, and discuss existing frameworks for engineering education in schools. We then describe four aspects of engineering fields, each uniquely characterized by the technology used and the artefact produced. Based on the work of previous studies (e.g., Erduran et al., 2019; Irzik & Nola, 2011; Kaya & Erduran, 2016), we propose the Family Resemblance Approach (FRA) as a methodological framework to analyze and develop the NOE pedagogical framework. In this paper, the conceptualization of NOE is developed within the FRA framework, while drawing on aspects of nature of science (NOS). The use of the FRA allowed us to anchor the theoretical discussion in a pedagogical context by drawing on aspects of NOS (Erduran, 2020; Erduran & Dagher, 2014) to provide examples for NOE-related learning assignments. Focusing on the cognitive and epistemic domain, the FRA was chosen since it includes both domain-general and domain-specific features that can highlight the way engineering education can be conceptualized. As such, it has the potential to inform characterization of NOE, while articulating the different aspects of the engineering enterprise (Erduran, 2020). Our approach is intended to provide some nuance to discussions about NOE in the context of engineering education in schools.

2.1 Engineering Education in Schools

In the last two decades, standards for engineering and technology education were presented in several reports (e.g., ITEA, 2007; NAGB, 2018; NGSS Lead States, 2013; NRC, 2009). For example, the Standards for Technological Literacy (STL) emphasized key elements of engineering design (ITEA, 2007). According to these standards, students are expected to apply a design process to solve problems in and beyond the laboratory classroom; specify criteria and constraints for the design; make two- and three-dimensional representations of the designed solution; test and evaluate the design in relation to preestablished requirements and refine as needed; and finally, generate a product and document the solution (ITEA, 2007). Another example is the *Next Generation Science Standards* (NGSS), which suggested the application of engineering concepts and practices to enhance students understanding of and interest in science (NGSS Lead States, 2013). According to these standards, students are expected to define the criteria and constraints of a design problem; evaluate competing design solutions; analyze data to identify the best solution; and develop a model of a proposed object, tool, or process such that an optimal design can be achieved.

The National Assessment Governing Board (NAGB, 2018) presented a range of education standards that address technology and engineering literacy. This includes references to systems thinking, maintenance and troubleshooting, construction and exchange of ideas and solutions, information research, and more. The standards' documents presented above are common in highlighting the importance of the engineering design process and its connection to science and mathematics education. This led to research involving students' engagement in design practices through various pedagogical approaches. For example, Mehalik et al., (2008) involved students in building electrical alarm systems using authentic engineering design practices. The study indicated that the systems design approach was helpful for gaining understanding of core science concepts and knowledge retention, especially among low-achieving students (Mehalik et al., 2008). The use of design activities was implemented in another study that examined ways to translate lessons learned in the science classrooms to engineering classrooms (Berland, 2013). The study explored the challenges associated with teaching science through design-based problems, presenting a guidance to curriculum development. Following this line of research, Cunningham et al., (2020) introduced the "Engineering is Elementary" program, designed to connect engineering and science practices. The study indicated a significant gain in students' understanding of engineering, technology, and science concepts.

Knowledge gains were indicated not only in science, but also in mathematics. Mousoulides and English (2009) integrated an engineering activity within the mathematics curriculum to provide an opportunity for students to apply mathematics while solving real-world problems (Mousoulides & English, 2009). Daugherty and Carter (2018) advocated the interdisciplinary pedagogical approach, by which students learn the interconnectedness of the disciplines of science, technology, engineering, and mathematics. The researchers maintained that this approach provides a platform to introduce students to engineering design, cooperative learning, and problem-solving capabilities. A recent study by Purzer et al. (2022) introduced the honeycomb of engineering framework, which illustrates the adaptability of design methodology through user-centered design, design-build-test, engineering science, optimization, engineering analysis, and reverse engineering. The study categorizes the multiple goals of engineering education while stressing that educators and researchers should be cautious against a monolithic definition of engineering (Purzer et al., 2022).

Even though engineering practices are emphasized in national standards and despite the promising results shown in recent studies (e.g., Cunningham et al., 2020; Daugherty & Carter, 2018; Purzer et al., 2022), engineering concepts are not common in science, technology, and mathematics documents and they are seldom practiced in classrooms (Carr et al., 2012; Ekiz-Kiran & Aydin-Gunbatar, 2021). To this day, many students complete K-12 education with little or no exposure to engineering education (Hammack & Ivey, 2017; Pleasants & Olson, 2019; Purzer, et al., 2022). The literature provides three main explanations for this phenomenon. First, there is a limited number of school teachers with an engineering background (Bybee, 2014; Purzer, et al., 2022), as those who hold an engineering degree rarely choose a teaching career. Teachers with little or no proper engineering education may not meet the requirements for teaching this subject (Hammack & Ivey, 2017; Purzer, et al., 2022). Second, there is a limited number of engineering education training programs for in-service and preservice teachers who, overall, have little or no knowledge of design-based practices (Ekiz-Kiran & Aydin-Gunbatar, 2021; NASEM, 2020; NRC, 2009). Third, engineering is a multifaceted discipline, requiring the application of high-level science and mathematics; hence, its instruction is particularly complicated (Barak & Usher, 2022; Honey et al., 2014; Pleasants et al., 2019).

2.2 Integration of Engineering into Science Curriculum and Pedagogy

The limited number of school teachers with engineering degrees and the packed curriculum that leaves little place for a new discipline led to the integration of engineering topics into existing science courses (Ekiz-Kiran & Aydin-Gunbatar, 2021; Johnston et al., 2019). The integrative and interdisciplinary approach has been advocated for several years (Brown et al., 2012; NRC, 2012). A key argument in the support of this approach is that it promotes science education through real-world applications (Barak, 2017; Honey, et al., 2014; Park et al., 2020). However, without proper preparation, science teachers might hold erroneous understandings about the engineering discipline, resulting in superficial instruction and shallow student learning (Honey et al., 2014; NASEM, 2020; Pleasants & Olson, 2019). Since most science teachers hold degrees in the sciences, concerns were raised about their lack of engineering background and understanding (Bybee, 2014; Purzer, et al., 2022).

Particular concerns were raised regarding science teachers' ability to differentiate between scientific inquiry and engineering design (Bybee, 2014; Mangiante & Gabriele-Black, 2020). In a study conducted by Hammack and Ivey (2017), science teachers self-reported on having little experience in engineering education and only few were able to distinguish between engineering and science activities. Other studies showed that science teachers, in general, are unfamiliar with engineering concepts and tend to hold stereotypical misconceptions about the work of engineers (Cunningham et al., 2006; Purzer, et al., 2022). Teachers were found to have limited awareness of the importance of engineering activities and partial understanding of ways to solve engineering problems. Some mistakenly regarded engineers as manual workers in auto-mechanics or construction (Hammack & Ivey, 2017; Pleasants & Olson, 2019). A study found that teachers were more likely to perceive engineers as people constructing a building than those who supervise the construction process (Cunningham et al., 2006). Overall, the literature shows that science teachers' perceptions of engineering and engineering design were not well aligned with the engineering practices and disciplinary core ideas described in reports such as the NRC (2009) or the NGSS Lead States (2013). Since teachers' conceptions (or misconceptions) have an impact on students' learning outcomes, there is a growing need for teacher development programs in engineering education (AE3 & ASEE, 2020; Deniz et al., 2020; Hammack & Ivey, 2017).

Several educational studies were conducted to propose pedagogical frameworks for engineering education in schools. Moore and colleagues (2014) suggested a framework designed to inform the structure of STEM education standards and initiatives. The framework for quality K-12 engineering education includes 12 key indicators, such as "processes of design" and "teamwork." According to the researchers, although clear distinctions were made between the indicators, their applications seem to overlap (Moore et al., 2014). Another example is the P-12 engineering learning framework (AE3 & ASEE, 2020), which was developed to identify learning goals that all students should reach to become engineering literate. This framework presents a taxonomy of engineering contents that emerged from a modified Delphi study. It details the engineering concepts, practices, and habits of mind; yet, it places little emphasis on connections to science education curricula (AE3 & ASEE, 2020). A more recent framework is the honeycomb of engineering framework, which provides a philosophical account of precollege engineering education (Purzer et al., 2022). The framework categorizes the various goals of engineering, while the fundamental practice of "design" is shared across various disciplines. According to the authors (Purzer et al., 2022), the framework can be used for lesson design but does not prescribe effective teaching. The framework also does not call for explicitly teaching the nature of engineering as a learning objective.

To address the shortage of engineering education programs for science teachers, the NASEM report (2020) suggests holding collaborative dialogues among experts from colleges of education, colleges of engineering, and other stakeholders. The report maintains that teacher education programs should identify and implement actions that underline the engineering components within the vision for school science education (NASEM, 2020). Teacher development programs should support the construction of deep pedagogical content knowledge in engineering, to avoid science and engineering to be conflated and confused (Antink-Meyer & Brown, 2019; Johnston et al., 2019; NASEM, 2020). Authentic representations of science and engineering in the classrooms require well-developed views of the nature of science as well as the nature of engineering (Erduran, 2020; Pleasants et al., 2019). According to the NASEM (2020) report, in order to build a capacity for teaching engineering in K-12 education, it is necessary to address the essential qualities of engineering, the design process, and core engineering concepts. The report calls for a nuanced conceptualization of "engineering" and its differentiation from "science" and "technology" (NASEM, 2020), themes that are discussed in the next section.

2.3 Differentiating Engineering from Science and Technology

Although linked, science, technology, and engineering have different and distinct cognitive and epistemology characteristics that should be identified and understood (Antink-Meyer & Brown, 2019; McComas & Burgin, 2020; NASEM, 2020). The related, but separate, nature of science, technology, and engineering disciplines necessitate a clear definition and differentiation (Ekiz-Kiran & Aydin-Gunbatar, 2021; McComas & Burgin, 2020). When engineering design tasks are introduced in science classrooms, the borders between the disciplines can become blurred, leading to conflations between the fields (Johnston et al., 2019; NASEM, 2020). Since science, engineering, and technology are interdependent disciplines, the framing of their relationships, in the context of school education, requires an in-depth examination.

The distinction between science and engineering or technology is relatively noticeable. Science is viewed as a systematic study of the natural and the physical world through methods such as observations, experiments, modeling, and classifications (NSTA & ASTE, 2019; NGSS Lead States, 2013). Science answers questions about the natural world, while engineering and technology promote the design and development of human-made world. The distinction between engineering and technology presents a greater challenge, given that they are used interchangeably to describe aspects of human-developed products. Engineering and technology represent high points of human achievement from an academic viewpoint as well as from a daily life perspective. The distinction between the two disciplines is important since their integration into the science curriculum requires a better understanding of each discipline from a theoretical and practical standpoint (NAGB, 2018; NASEM, 2020).

According to the National Assessment Governing Board (2018), engineering is defined as "*a systematic and often iterative approach to designing objects, processes, and systems to meet human needs and wants*" (NAGB, 2018, p. 5). Whereas, technology is perceived as "*…products, processes, and systems created by people to meet human needs and desires*" (NAGB, 2018, p. 23). Pleasants and Olson (2019) maintain that the engineer works with nature and its laws as revealed by science, whereas the technologist focuses more on the actual construction. Engineering is viewed as a creative problem-solving process that involves testing and revisions (e.g., designing a device that can be used as a phone, a camera, and a music player), while technology is viewed as the means to solve the problem (e.g., machines on the production line) as well as the end product (e.g., mobile phones). In short, the connections and distinctions between the three disciplines can be summarized as follows: Guided by *science* rules and principles, *engineering* involves the knowledge and practices required for designing new or improved *technologies* (NAGB, 2018; NASEM, 2020). With appropriate support and guidance, science teachers with little or no formal engineering education can develop understanding of engineering (e.g., Deniz et al., 2020; Pleasants & Olson, 2019). This reinforces the importance of developing a conceptual framework of the nature of engineering from cognitive and epistemic lenses (Pleasants & Olson, 2019; Purzer et al., 2022). In proceeding this mission, it also becomes imperative to highlight the key aspects of different engineering fields.

2.4 Key Aspects of Engineering Fields

Although there is an increasing interest in engineering education in the context of science education, engineering is often presented in a fairly broad manner without much distinction drawn across the aspects of different sub-fields of engineering. For example, Purzer et al. (2022) highlight that in the case of NGSS, practices are not differentiated relative to engineering. With the purpose of catering to human needs, engineering focuses on the design and creation of new or improved artefacts. The word “artefact” originates from Latin as a combination of Arte—‘by skill’, and Factum—‘to make.’ ‘Artefact’—the skill of making something new, refers to an object that is generated and used for a purpose. Engineering artefacts have expanded to include not only tangible machinery and tools, but also computer software, design documents, written patents, and even subcellular nanorobots. Over the years, engineering has split into fields and sub-fields, with different areas of specialization such as civil, environmental, chemical, mechanical, computer, and aerospace (ABET, 2019; ITEA, 2007; NASEM, 2020). Based on the created artefacts, engineering in general can be divided into four main categories: Structures, Machines, Materials, and Data as described below.

Structures Engineering fields that involve the planning and constructing of buildings and infrastructures to accommodate human needs and solve societal problems (ABET, 2019; NASEM, 2020). Building structures is the oldest engineering practice, dated back to the construction of the pyramids in ancient Egypt and aqueducts in ancient Rome. It involves identifying the purpose and functionality of the structure and the forces that act upon it. It also involves identifying the suitable construction materials and their correct proportions to withstand operational load, weather damage, earthquakes, and other internal and external forces. Such structures include buildings, roads, railways, sewage systems, and dams. The design and development of structures is typical to civil engineering and architectural engineering.

Machines Engineering fields that involve the use and development of complex devices and tools assembled from mechanical parts in order to perform particular tasks through the application of power transition (ABET, 2019; ITEA, 2007). This includes mechanical transmission, using gears, rods, and straps; electric transmission, using electrical energy; hydraulic transmission, using fluids such as water or oil as a working mechanism; and pneumatic transmission, using compressed gas, usually air. Developing mechanical devices can be found in many engineering fields, but it is typical to mechanical engineering, biomedical engineering, and aerospace or naval engineering (ITEA, 2007; NASEM, 2020). These engineering fields involve the generation of engines, pumps, levers, as well as boats, vehicles, aircrafts, heating and cooling systems, robots, etc.

Materials Engineering fields that involve the use and manipulation of materials in the form of solids, liquids, gases, and other condensed phases, to develop useful products. This ranges from large-scale chemical processes to microorganisms and nanomaterials that are utilized for certain applications (ITEA, 2007; NASEM, 2020). In the early stages, it was based on the petrochemical industry, involving processes such as crystallization, evaporation, oxidation, and hydrocracking (ABET, 2019). When the pharmaceutical and food industries became prominent, it involved the manufacturing of products such as drugs and canned food. Nowadays, there are industries that create and use polymers, ceramics, metals, radioactive alloy, as well as advanced materials such as semiconductors and nanomaterials. Engineers partake in designing, analyzing, modeling, and controlling mass production of materials such as detergents, fertilizers, food, and medicine. The creation and use of materials is typical to chemical engineering, martial engineering, nuclear engineering, genetic engineering, and food engineering.

Data Engineering fields that involve the development and use of computer-based data, creating and manipulating electrical signals in the form of symbols, figures, or characters (ABET, 2019; ITEA, 2007). Through a sequence of instructions named "algorithm," engineering fields use the binary coding system of zeros and ones to compute and process data in a central processing unit and store them on hard disks or servers. This relatively new field of engineering involves data analysis and design techniques that are used for the understanding of operational processing (ABET, 2019; NASEM, 2020.) It focuses on data formats, scaling, and security, translating data into insights. Data engineers are involved in the synthesis, encoding and decoding of digital signals, and transmitting or receiving data from various sources such as global positioning systems. They are involved in the creation of software, control systems, cyber security, artificial intelligence, and more. The creation and use of computerized data can be found in many engineering fields, but it is most typical to computer engineering, electric engineering, and systems engineering.

The discussion on existing frameworks for engineering education in schools and the description of key aspects of engineering fields provide an overview of the importance of generating a pedagogical framing of NOE (Antink-Meyer & Arias, 2022; Deniz et al., 2020; Pleasants & Olson, 2019). These educational and disciplinary frameworks afford a view of engineering as a set of pedagogical components and indicators, with little reference to a holistic conceptualization of the NOE. Studies advocate for both the conceptualization and explicit instruction of the NOE as means for developing in-depth understanding of engineering literacy (Antink-Meyer & Arias, 2022; Pleasants & Olson, 2019). Our claim is that in order to function successfully in our global and technology-saturated world, the instruction of the NOE should be a significant component of school education. However, providing a comprehensive definition of NOE and generating reliable tools to teach and assess are yet one of the main challenges of educational systems worldwide (Antink-Meyer & Arias, 2022; NASEM, 2020). In addition, while elaborating on the pedagogical benefits of engineering learning, less attention was devoted to cognitive and epistemological typology of engineering practices (Purzer et al., 2022). Based on the work of previous studies (Erduran et al., 2019; Irzik & Nola, 2011; Kaya & Erduran, 2016), this paper draws upon the Family Resemblance Approach (FRA) as a methodological framework to analyze and develop the NOE framework.

3 Framing the NOE through the Lens of the Family Resemblance Approach

In the last decade, the Family Resemblance Approach (FRA) has served as a framework for holistic conceptualization of nature of science (Irzik & Nola, 2011). Studies use the FRA to provide a flexible and unifying framework for promoting a broad and inclusive account of nature of science (NOS) for science education (e.g., Erduran & Dagher, 2014; Erduran et al., 2019; Kaya & Erduran, 2016). FRA has been expanded for research application, focusing on the nature of STEM disciplines (Park et al., 2020). The FRA considers a discipline, such as "science," as a family concept, whose subdomains resemble one another with respect to several key aspects. It acknowledges common features of subdomains, while at the same time accommodates disciplinary particularities (Irzik & Nola, 2011; Kaya & Erduran, 2016). While research has established the pedagogical benefits of teaching engineering in schools, the cognitive and epistemic foundations of NOE remain under-examined (Pleasants & Olson, 2019). To illustrate the affordance of FRA in characterizing NOE, we provide an analysis of the literature, focusing on the "cognitive and epistemic" domain, which according to the work of Erduran & Dagher (2014) includes four categories: Aims & Values, Practices, Methods & Methodological Rules, and Knowledge.

In the following sections, NOE is situated in a pedagogical framework based on the FRA cognitive and epistemic domains. Drawing from recommendations made by updated literature, we situate each FRA category within the context of policy reports, such as NGSS Lead states (2013) and the report of the National Science Teaching Association & Association for Science Teacher Education (NSTA & ASTE, 2019). Each category is also situated within the context of research and policy reports on engineering education, such as the National Academies of Sciences, Engineering, and Medicine (NASEM, 2020), the National Academy of Engineering (NAE, 2010), and/or the National Assessment Governing Board (NAGB, 2018) on Technology & Engineering Literacy. The following sections apply each of the four FRA categories to the work of engineers and to engineering fields and practices, with educational applications and examples of assignments for students.

3.1 Aims & Values

Aims and values are significant as they provide a foundation upon which people act. According to research and policy reports scientists and engineers rely on human qualities such as persistence, precision, reasoning, logic, imagination, and creativity (AE3 & ASEE, 2020; NGSS Lead states, 2013). Also, scientists and engineers are guided by habits of mind such as intellectual honesty, tolerance of ambiguity, skepticism, and openness to new ideas (NASEM, 2020; NSTA & ASTE, 2019). The main aim of the engineering enterprise is designing and maintaining products, structures, and data systems, looking for new opportunities while adhering to market needs. Engineering aims at modifying the world and widening the prospects of contemporary society through innovation and technological development (Barak & Usher, 2019; Kroes, 2012). In view of this, a question arises as to the values of the engineering enterprise that can be deduced. Discussing the aims and values of science, Erduran and Dagher (2014) put forward the idea that within the cognitive and epistemic domain, the scientific enterprise is underpinned by seven main tenets: (a) objectivity—seeking neutrality and avoiding bias, (b) novelty—searching for new explanations, (c) accuracy—ensuring that explanations are accurate, (d) empirical adequacy—basing claims on relevant and plausible data, (e) critical examination—giving reasons to justify claims, (f) addressing anomalies—recognizing opposite ideas and responding to objections, and (g) taking challenges—addressing opposition to own ideas seriously (Erduran & Dagher, 2014; Erduran et al., 2020). These aims and values can be attributed to engineering; however, while science's main goal is building knowledge of the natural world regardless of applications, engineering revolves around improving or creating new artefacts, with an emphasis on commercial applications. Thus, it is important to discuss nuanced differences.

From an engineering perspective, *objectivity* refers to applying an objective and rational approach to the design process, using mathematics and scientific laws to solve engineering challenges (Pleasants et al., 2019; Poel, 2015). *Novelty* refers to generating creative ideas, in an agile manner, and turning them into practical and efficiently implementable solutions (Antink-Meyer & Brown, 2019; Barak & Usher, 2019). *Accuracy* refers to ensuring that the design and implementation processes are accurate and precise (NAGB, 2018). Inaccurate calculations have led to disasters, such as the case of the collapse of the Hyatt

Hotel walkway in Kansas City in 1981 or the explosion of the Challenger Space Shuttle in 1986. *Adequacy* refers to designing artefacts that are relevant to societal needs, generating technological solutions that add value to society (Antink-Meyer & Brown, 2019; Barak & Usher, 2019). *Critical examination* refers to evaluating the compatibility and quality of the design process, the modeling method, and the final product, conducting systems analysis, and making decisions (Poel, 2015; Violante & Vezzetti, 2017). *Addressing anomalies* refers to choosing the most suitable solution within limitations imposed by resources, technology, safety, and cost, providing reliable and robust solutions to an engineering problem (NAGB, 2018; Pleasants & Olson, 2019). *Taking challenges* seriously refers to addressing financial, environmental, social, and ethical constraints to generate sustainable engineering outcomes (NAGB, 2018; NASEM, 2020). The different perspectives of the aims and values of science and engineering education are summarized in Table 1.

3.2 Engineering Practices

Scientific and engineering practices are emphasized in the Framework for K-12 Science Education together with disciplinary core ideas and crosscutting concepts (NGSS Lead States, 2013; NRC, 2012). Erduran & Dagher, (2014) used the analogy of a benzene ring to illustrate the heuristics of scientific practices as being linked in one holistic representation. Based on this analogy, Erduran and Dagher (2014) present six heuristic features: real world, activities, data, model, explanation, and prediction. Integral to and interacting with the six features are representation, reasoning, discourse, and social certification, which are presented in the middle of the ring model (e.g., Erduran et al., 2020; Erduran & Dagher, 2014). This analogy of the heuristics of scientific practices raised the question: Can engineering-related practices be presented in a similar way?

Similar to science, the engineering enterprise encompasses a wide range of cognitive, epistemic, and discursive practices. Such practices involve the structures and systems engineers use for designing a new or improved artefact. The “ring” analogy is relevant to engineering practices, as they involve in an iterative process of solving human-related problems based on deep scientific and mathematical knowledge (NAE, 2010; NAGB, 2018). The NGSS framework (2013) refers to eight science and engineering practices. If we focus our attention on engineering-related practices, they include (P1) Defining problems; (P2) Developing and using (engineering) models; (P3) Planning and carrying out investigations; (P4) Analyzing and interpreting (engineering) data; (P5) Using mathematics and computational thinking; (P6) Designing solutions; (P7) Engaging in argument from evidence; and (P8) Obtaining, evaluating, and communicating information. These practices require a meta-level of understanding, which aligns with the FRA framework.

According to engineering education literature (e.g., NAE, 2010; NAGB, 2018), engineering practices involve activities such as identifying a problem and/or an opportunity; defining specifications, requirements, and constraints; performing analysis; using research and brainstorming techniques to generate ideas for possible solutions; evaluating each solution against requirements, considering risks and making trade-offs; producing high-quality solutions under the given circumstances; building and testing of prototypes (physical or mathematical models); and designing alternatives for further development. Engineering practices involve a complex process of balancing competing criteria of desired functions, technological feasibility, cost, safety, aesthetics, and compliance with legal requirements (NGSS Lead States, 2013). Adapting the scientific heuristics to engineering practices, we suggest the analogy of a hex nut—a six-sided nut that is commonly used in the industry

Table 1 The aims and values of science vs. engineering education

Aims and values	Science educational application (from Erduran & Dagher, 2014)	Engineering educational application
Objectivity	Seeking neutrality and avoiding bias	Seeking objective and applying a rational approach to the design process
Novelty	Searching for new explanations	Searching for creative ideas in an agile manner, generating practical and efficiently implementable solutions
Accuracy	Ensuring that explanations are accurate	Ensuring that the design and implementation processes are accurate and precise
Adequacy	Basing claims on relevant and plausible data	Designing artefacts that are relevant to societal needs, generating technological solutions that add value to society
Critical examination	Giving reasons to justify claims	Evaluating the compatibility and quality of the design process, the modeling, method, and the final product, conducting systems analysis, and making decisions
Addressing anomalies	Recognizing opposite ideas and responding to objections	Recognizing the most suitable solution within limitations imposed by resources, technology, safety, and cost
Taking challenges seriously	Addressing opposition to own ideas seriously	Addressing financial, environmental, social, and ethical constraints to generate sustainable engineering outcomes

with machines. Each side in the hexagonal structure represents an engineering practice of P1 to P6. In the middle of the model are P7 and P8, which are integral to and interacting with the six engineering practices. Table 2 presents the heuristic features, engineering-related practices, and example assignments.

Table 2 shows that while most of the heuristics of scientific practices, proposed by Erduran and Dagher (2014), are relevant to engineering practices, there are some differences. The similar heuristic features are Real world, Activities, and Model, which describe the three engineering practices (P1–P3). The Data feature is also similar in describing two practices: Analyzing and interpreting data (P4) and Using mathematics and computational thinking (P5) to assess resources and solutions. The difference lies in assigning P6 to the Design feature, while Erduran and Dagher (2014) assigned it to Explanation. This can be explained by the differentiation made by the NGSS framework (2013), which presents P6 as "Constructing an explanation (for science) and designing a solution (for engineering)." The second difference lies in the Production feature that is an important aspect of engineering, but not explicitly mentioned as part of the eight science and engineering practices (NGSS Lead States, 2013). The engineering "Production" feature replaces the Prediction feature (Erduran & Dagher, 2014), which corresponds with scientific practices. Nevertheless, both features are related since successful production of engineering products requires good predictions of technological trends and market feasibility.

For teaching and learning purposes, this framework may engage students in engineering-related practices such as identifying a real-world problem, defining specifications and constraints, indicating possible solutions, performing simulations to assess available resources, balancing resource, decision making, and more. The application of engineering heuristics engages students in analytical and systemics thinking, creativity, and innovation (Barak & Yuan, 2021; Barak & Usher, 2022). When practiced in team projects, it can engage learners in knowledge-sharing and collaboration (Barak & Usher, 2022), as well as develop unique skills such as leadership, dealing with failure, and professional ethics. This framework has the potential to unify the targeted cognitive and epistemic aspects of engineering practices so that they are implemented in a holistic and coherent manner at different levels of science and engineering education.

3.3 Methods & Methodological Rules

Methods and methodological rules refer to the variety of systematic guidelines and approaches that scientists use to ensure that their investigative outcomes produce accurate and reliable knowledge (Erduran & Dagher, 2014; Irzik & Nola, 2011). Science is based on the idea that it is a structured activity, regulated by methodological rules, and that scientists use a variety of methods to solve different research problems. When it comes to science education, there are pedagogical heuristics and conceptual tools to engage students in discussions on scientific methods and methodological rules (e.g., Erduran et al., 2020). Instructional tools were developed to foster students' understanding of the different types of scientific methods and their contribution to the construction of theories. However, it is still unclear whether these epistemic ideas and pedagogical heuristics are true or relevant to engineering education. Engineering and science are perceived as similar in that both involve creative processes, and neither uses just one method (NRC 2012, p. 46). However, study caution against teaching the engineering design process as a list of linear steps (Deniz et al., 2020; Pleasants & Olson, 2019).

Table 2 Heuristic features, engineering-related practices, and example assignments

Heuristic features	Engineering practices (NGSS Lead States, 2013)	Assignments for students
Real world	P1. Defining human-related problems	Identify a problem, a need, and/or an opportunity
Activities	P3. Planning and carrying out investigations	Define specifications, requirements and constraints
Model	P2. Developing and using engineering models	Indicate possible solutions against requirements using engineering models
Data	P4. Analyzing and interpreting data P5. Using mathematics and computational thinking	Perform data analysis by using mathematics and computerized simulations to assess available resources, safety, and cost
Design	P6. Designing solutions	Identify the best solution and plan a prototype in detail
Production	?	Produce the designed prototype
Reasoning, discourse	P7. Engaging in argument from evidence	Use research and brainstorming techniques to evaluate the prototype
Representation, social certification	P8. Obtaining, evaluating, and communicating information	Test and improve the prototype, suggest a marketing strategy and an advertising campaign

As pre-college engineering education is gaining interest among educators, it is important to discuss questions such as: What are the methods and methodological rules applied to engineering? What methods are best suited for engineering? Do different engineering fields have different methods and methodological rules? What pedagogical frameworks can be used for learning about engineering methods and methodological rules? There is agreement on the need to promote school students' understanding of engineering (Berland, 2013; Mehalik et al., 2008; NGSS Lead States, 2013). However, answering the questions posed above is an on-going challenge as engineering is a multifaceted discipline that involves many fields that are based on different sets of methods and rules (English & Moore, 2018; Kroes, 2012; Mitcham & Schatzberg, 2009).

As inquiry is viewed as a representation of the scientific method, simplistic as it may be, the design process is the prevalent representation of the engineering method. Engineering design is viewed as the method used to identify and solve problems to meet human needs. Different engineering fields use different design methods, but there are some common attributes. The Engineering is Elementary program (Cunningham et al., 2020) introduces an engineering design process that includes five steps: ask, imagine, plan, create, and improve. Berland (2013) describes a multi-level representation of the design process based on 11 different models of engineering design. This representation includes five "super-steps": identify, describe, generate, embody, and finalize, underlining that design solutions evolve over time. A more sophisticated illustration of the design process is presented by ABET (2019), which includes several iterative steps, such as identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade-offs, for the purpose of obtaining a high-quality solution under the given circumstances. This representation illustrates the nonlinear nature of the engineering design process.

In the context of pre-college engineering education, discussions of the engineering methods and methodological rules should consider the history and the philosophy of this profession. As engineering is a multifaceted profession, educators should strive to convey its complexities. There is a need to develop instructional tools to foster students' understanding of the different types of engineering methods and their contribution to the creation of new or improved artefacts (Barak & Usher, 2022; Honey et al., 2014). Similar to scientific methods, engineering methods should be perceived as a creative process that involves the use of more than just one approach. It is important to build students' understanding of engineering design as a nonlinear process through pedagogical heuristics. Epistemic ideas relevant to engineering education may include design methods grouped into four types of artefacts: Materials, Machines, Structures, and Data. With regards to Materials, as in chemical engineering, or Machines, as in mechanical engineering, *biomimetic design* is based on mimicking natural materials, mechanisms, and processes that are found in nature, to solve human design challenges. The design methods can resemble elements from nature "look like" and/or focus on function "work like." For example, the biomechanics of the gecko lizard's toes have inspired a host of climbing materials and the efficiency at which the whales swim has inspired the design of serrated-edge wind turbines. With regards to Structures, the *Mixed-Use Design* is applied in sustainable architecture and urban planning, by integrating three or more uses into one structure such as transportation, residential, hotel, retail, entertainment, and parking. This design method focuses on maintaining quality of life while minimizing the impact on the environment. Other design methods include the *Design for Assembly* and the *Reverse Engineering* method. In the *Design for Assembly* method, artefacts are produced by bringing together existing components with fewer parts and ease of assembly in mind. This method is common in computer design, as it allows flexibility in integrating components in various positions. An example is the Sony SMART assembly system, a robotic system for assembling small devices. The *Reverse Engineering* method is a process that takes an existing product, disassembles its components, analyzes them, and builds a similar product accordingly. Throughout history, nations and private companies have reversed engineered parts of aircrafts, missiles, vehicles, hardware, software, and more.

3.4 Engineering Knowledge

While scientific knowledge is regarded as the "end-product" of scientific activity (Erduran & Dagher, 2014; Irzik & Nola, 2011), engineering knowledge is an outgrowth of the design and manufacturing processes (NAGB, 2018; NASEM, 2020). Engineering knowledge consists of a combination of scientific and mathematical theories, laws, and models that are the basis of all engineering practices (NAE, 2010; NAGB, 2018). It includes practical applications of the engineering enterprise that generate and/or validate engineering concepts. Engineering knowledge provides logical and systematic descriptions of how human-made artefacts work, opening the possibility for innovations and further developments (Barak & Usher, 2019, 2022). Engineers are required for wide-ranging knowledge and analytical skills to bring innovation and engage with problem-solving. Engineering knowledge results in products that are tangible (i.e., vehicles, robots, computers, etc.) and/or intangible (written patents, lines of codes, system design models, etc.).

Engineering knowledge is directly connected to scientific theories, laws, and models. For example, when engineers engage in design, they draw on theories in thermodynamics, Newton's laws, and models of material strength. Often, engineers work within a well-explored technological area, connecting between known theories and unknown technological spaces. Yet, for science, knowledge about natural phenomena is an outcome in itself, while for engineering, knowledge is a means for designing new artefacts. Scientists strive to generate new knowledge and gain the recognition of the scientific community, while engineers are more concerned about registering patents and protecting new knowledge from industrial espionage. Engineering knowledge can be discipline specific, but it can also be seen as a holistic conceptualization of answers to how things can be further developed or significantly improved (Barak & Usher, 2022). With a focus on innovation, engineering knowledge leads to and is the result of the design process, as new or improved ideas and artefacts are generated (Barak & Usher, 2019, 2022).

Engineering knowledge is associated with engineering practices and design activities (Antink-Meyer & Brown, 2019; Fleer, 2022; Mehalik et al., 2008). It focuses on how particular artefacts function or on analytical models that can be applied to a range of technologies (Pleasants & Olson, 2019). Drawing on an extensive body of literature, Pleasants and Olson (2019) presented nine disciplinary features of engineering for K-12 education, among which are knowledge production in engineering, sources of engineering knowledge, and models of design processes. The authors raise questions such as: What kinds of knowledge are internal to the engineering discipline? In what ways is engineering science different from, and similar to, natural science? How well do models of the design process capture the real work of designers? Elaborating on the work of Pleasants and Olson (2019), Antink-Meyer and Brown (2019) presented a set of seven features of nature of engineering knowledge, which are as follows: Empirical; Contextually responsive; Social; Personal; Societal and cultural; Interdisciplinary; Solution-oriented. It is maintained that the understanding of these features is fundamental for K-12 teachers who have limited engineering knowledge and experience. It is also asserted that the seven features contextualize engineering in relation to science, technology, and society, and that they are accessible without oversimplifying engineering. The frameworks presented above are valuable starting points for further discussions and refinements of the NOE construct within the research community. However, going beyond engineering content knowledge, questions such as: What engineering laws, theories, and models should be taught? and How should we teach them? are still relevant and should be further discussed and examined.

Theories, laws, and models are three entities that work together in providing a framework for cognitive and epistemic understanding of accumulated knowledge (Erduran & Dagher, 2014; Erduran et al., 2020). Erduran and Dagher (2014) maintain that as information gathers, the three entities become extended, contributing to further understanding in an iterative way. With regards to engineering, the literature points to the importance of discussing the epistemological nature of engineering knowledge (Antink-Meyer & Arias, 2022; Fleer, 2022), shedding light on the connection between theories, laws, and models. From a heuristic viewpoint, it is important to focus attention on the cognitive and epistemic aspects of the three entities, as meta-perspectives on engineering knowledge tend to be limited in schools (Carr et al., 2012; Ekiz-Kiran & Aydin-Gunbatar 2021; Purzer, et al., 2022).

4 Discussion and Implications

As engineering literacy is central to learning and working in our technology-oriented society, precollege engineering education has been the subject of recent policy reports and studies (AE3 & ASEE, 2020; Antink-Meyer & Brown, 2019; English & Moore, 2018). Studies point to the need for an ontological and pedagogical framing of the nature of engineering (NOE) and its integration into the science curriculum (Antink-Meyer & Arias, 2022; Deniz et al., 2020; Pleasants & Olson, 2019). Similar to the idea that science learning is enriched by deep understanding of the NOS (Dagher & Erduran 2016; Erduran et al., 2019), it is important to generate an ontological foundation of engineering, focusing on how engineers from different fields use cognitive and epistemic viewpoints in their work. In this paper, we suggest a new perspective to resolve the ongoing debate on the NOE heuristics and applications, by conceptualizing it as analogous to NOS. The complexity of theorizing NOE lies in that engineering is viewed as either a process, a field, and/or an approach (Antink-Meyer & Brown, 2019). It also lies in the ability to identify cognitive and epistemology characteristics that differentiate as well as connect engineering to scientific fields (Antink-Meyer & Brown, 2019; McComas & Burgin, 2020; NASEM, 2020). Thus, theorizing the NOE is important to the development of both engineering literacy and scientific literacy, as teaching them in tandem can promote deep understanding of modern society (Antink-Meyer & Arias, 2022; Pleasants & Olson, 2019).

Building on the Family Resemblance Approach (FRA) as characterised by Erduran and Dagher (2014), this paper describes NOE through four cognitive and epistemic categories: Aims & Values, Engineering Practices, Methods & Methodological Rules, and Engineering Knowledge. The framing of NOE through the use of the FRA categories can guide teaching and learning about engineering by providing a methodological lens through which engineering education can be developed in schools. It can be applied in teacher education programs to introduce the multifaceted nature of engineering. It can also support teachers in the process of selecting and presenting NOE-related learning materials, while aligning them with educational goals. Overall, the four FRA's cognitive and epistemic categories have a significant role in providing a clear and unified conceptualization of NOE, enabling a shared view of the engineering enterprise among educational stakeholders. Our underlying stance is that the cognitive and epistemic dimensions of NOE are central to the holistic understanding of engineering and the theoretical and practical relationships between engineering and science.

In the last decade, reports underlined the importance of framing and outlining the NOE and the role of engineers (NAE, 2010; NAGB, 2018). Theorizing the NOE is important to the development of engineering literacy as well as scientific literacy since teaching them in tandem can promote deep understanding of modern society (Antink-Meyer & Arias, 2022; Pleasants & Olson, 2019). The complexity of theorizing NOE lies in that engineering can be conceptualized as either a process, a field, and/or an approach (Antink-Meyer & Brown, 2019). Building on the family resemblance approach, this paper provides a framework for a continuous discussion on NOE and the theoretical and practical relationships between NOS and NOE. The framing of NOE through the use of FRA offers a lens that can be applied in teacher education programs to introduce the multifaceted nature of engineering. It can support teachers in the process of selecting and presenting the NOE-related learning materials, while aligning them with their educational goals. Our underlying stance is that cognitive and epistemic dimensions of NOE are central to the holistic understanding of engineering. The generation of a clear and unified conceptual framework of NOE may enable a shared view of the engineering enterprise among educational stakeholders. Such conceptualization can provide a lens through which engineering education can be developed in schools.

Author Contribution All authors contributed to the study conception, design, and implementation. All authors read and approved the final manuscript.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

References

Accreditation Board for Engineering and Technology [ABET] (2019). Criteria for accrediting engineering programs. Retrieved May 5, 2022, from https://www.abet.org/wp-content/uploads/2020/09/EAC-Criteria-2020-2021.pdf. Accessed 5 May 2022.

Advancing Excellence in P–12 Engineering Education, & The American Society for Engineering Education [AE3 & ASEE]. (2020). Framework for P–12 engineering learning: A defined and cohesive educational foundation for P–12 engineering. *Washington, DC: American Society for Engineering Education.* https://doi.org/10.18260/1-100-1153-1

Antink-Meyer, A., & Brown, R. A. (2019). Nature of engineering knowledge: An articulation for science learners with nature of science understandings. *Science & Education, 28*(3–5), 539–559.

Antink-Meyer, A., & Arias, A. M. (2022). Teachers' incorporation of epistemic practices in K-8 engineering and their views about the nature of engineering knowledge. *Science & Education, 31, 357–382.*

Barak, M. & Usher, M. (2019). The innovation profile of nanotechnology team projects of face-to-face and online learners. *Computers & Education, 137*, 1–11.

Barak, M. & Usher, M. (2022). The innovation level of engineering students' team projects in hybrid and MOOC environments. *European Journal of Engineering Education, 47*(2), 299–313.

Barak, M. & Yuan, S. (2021). A cultural perspective to project-based learning and the cultivation of innovative thinking. *Thinking Skills and Creativity, 39*, 100766. https://doi.org/10.1016/j.tsc.2020.100766

Barak, M. (2017). Science teacher education in the twenty-first century: A pedagogical framework for technology-integrated social constructivism. *Research in Science Education, 47*(2), 283–303.

Berland, L. K. (2013). Designing for STEM education. *Journal of Pre-College Engineering Education Research, 3*(1), 22–31.

Bybee, R. W. (2014). NGSS and the next generation of science teachers. *Journal of Science Teachers Education, 25*, 211–221.

Carr, R. L., Bennett, L. D., & Strobel, J. (2012). Engineering in the K-12 STEM standards of the 50 U.S. states: An analysis of presence and extent. *Journal of Engineering Education, 101*(3), 539–564.

Cunningham, C. M., Lachapelle, C. P., Brennan, R. T., Kelly, G. J., Tunis, C. S. A., & Gentry, C. A. (2020). The impact of engineering curriculum design principles on elementary students' engineering and science learning. *Journal of Research in Science Teaching, 57*(3), 423–453.

Cunningham, C. M., Lachapelle, C., & Lindgren-Streicher, A. (2006). Elementary teachers understanding of engineering and technology. Proceedings of the American Society for Engineering Education American Conference and Exposition (Vol. 113). ASEE.

Dagher, Z. R., & Erduran, S. (2016). Reconceptualizing the nature of science for science education. *Science & Education, 25*(1-2), 147–164.

Daugherty, M. K., & Carter, V. (2018). The nature of interdisciplinary STEM education. In M. J. de Vries (Ed.), *Handbook of technology education* (pp. 159–172). Springer.

Deniz, H., Kaya, E., Yesilyurt, E., & Trabia, M. (2020). The influence of an engineering design experience on elementary teachers' nature of engineering views. *International Journal of Technology and Design Education, 30*, 635–656.

Ekiz-Kiran, B., & Aydin-Gunbatar, S. (2021). Analysis of engineering elements of K-12 science standards in seven countries engaged in STEM education reform. *Science & Education, 30*, 849–882.

English, L. D., & Moore, T. (Eds.) (2018). *Early engineering learning*. Springer.

Erduran, S. (2020). Nature of "STEM"? Epistemic underpinnings of integrated science, technology, engineering, and mathematics in education. *Science & Education, 29*, 781–784.

Erduran, S., & Dagher, Z. (2014). *Reconceptualizing the nature of science for science education*. Dordrecht: Springer.

Erduran, S., Dagher, Z. R., & McDonald, C. V. (2019). Contributions of the family resemblance approach to nature of science in science education. *Science & Education, 28*(3), 311–328.

Erduran, S., Kaya, E., Cilekrenkli, A., Akgun, S., & Aksoz, B. (2020). Perceptions of nature of science emerging in group discussions: A comparative account of pre-service teachers from Turkey and England. *International Journal of Science and Mathematics Education*. https://doi.org/10.1007/s10763-020-10110-9

Fleer, M. (2022). A cultural-historical critique of how engineering knowledge is constructed through research in play-based settings: What counts as evidence and what is invisible? *Research in Science Education, 52,* 1355–1373.

Hammack, R., & Ivey, T. (2017). Elementary teachers' perceptions of engineering and engineering design. *Journal of Research in STEM Education, 3*, 48–68.

Honey, M., Pearson, G., & Schweingruber, A. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. National Academies Press.

International Technology Education Association [ITEA] (2007). *Standards for technological literacy: Content for the study of technology*, 3rd ed. International Technology Education Association. Retrieved May 5, 2022, from https://www.iteea.org/File.aspx?id=67767v&v=b26b7852. Accessed 5 May 2022.

Irzik, G., & Nola, R. (2011). A family resemblance approach to the nature of science for science education. *Science & Education, 20*(7), 591–607.

Johnston, A. C., Akarsu, M., Moore, T. J., & Guzey, S. S. (2019). Engineering as the integrator: A case study of one middle school science teacher's talk. *Journal of Engineering Education, 108*(3), 418–440.

Kaya, E., & Erduran, S. (2016). From FRA to RFN, or how the family resemblance approach can be transformed for science curriculum analysis on nature of science. *Science & Education, 25*(9–10), 1115–1133.

Kelly, G., & Green, J. (Eds.). (2018). *Framing issues of theory and methods for the study of science and engineering education*. Routledge.

Kroes, P. (2012). *Technical artefacts: Creations of mind and matter: A philosophy of engineering design*. Springer.

Mangiante, E. S., & Gabriele-Black, K. A. (2020). Supporting elementary teachers' collective inquiry into the "E" in STEM. *Science & Education, 29*, 1007–1034.

McComas, W. F., & Burgin, S. R. (2020). A critique of "STEM" education. *Science & Education, 29*, 805–829.

Mehalik, M. M., Doppelt, Y., & Schuun, C. D. (2008). Middle-school science through design-based learning versus scripted inquiry: Better overall science concept learning and equity gap reduction. *Journal of Engineering Education, 97*(1), 71–85.

Mitcham, C., & Schatzberg, E. (2009). Defining technology and the engineering sciences. In A. Meijers (Ed.), *Philosophy of technology and engineering sciences* (pp. 27–63). Elsevier.

Moore, T. J., Glancy, A. W., Tank, K. M., Kersten, J. A., Smith, K. A., & Stohlmann, M. S. (2014). A framework for quality K–12 engineering education: Research and development. *Journal of Pre-College Engineering Education Research, 4*(1), 2. https://doi.org/10.7771/2157-9288.1069

Mousoulides, N., & English, L. D. (2009). Integrating engineering experiences within the elementary mathematics curriculum. In L. Mann & R. Hadgraft (Eds.), *Proceedings of the 2nd research in engineering education symposium*. University of Melbourne: Melbourne School of Engineering.

National Academies of Sciences, Engineering, and Medicine [NASEM]. (2020). *Building capacity for teaching engineering in K-12 education*. The National Academies Press. https://doi.org/10.17226/25612

National Academy of Engineering [NAE]. (2010). *Standards for K-12 engineering education?* Committee on Standards for K-12 Engineering Education. The National Academies Press.

National Assessment Governing Board [NAGB]. (2018). *Technology & engineering literacy framework for the 2018*. National Assessment of Educational Progress. Retrieved May 5, 2022, from http://files.eric.ed.gov/fulltext/ED594359.pdf. Accessed 5 May 2022.

National Research Council [NRC]. (2009). *Engineering in K-12 education: Understanding the status and improving the prospects*. The National Academies Press.

National Research Council [NRC]. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas.* Committee on a Conceptual Framework for New K-12 Science Education Standards. Board on Science Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

National Science Teaching Association [NSTA] and Association for Science Teacher Education [ASTE] (2019). *2020 NSTA/ASTE Standards for Science Teacher Preparation*. Retrieved May 5, 2022, from http://static.nsta.org/pdfs/2020NSTAStandards.pdf.

Next Generation Science Standards [NGSS] Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: The National Academies Press.

Park, W., Wu, J. Y., & Erduran, S. (2020). The nature of STEM disciplines in the science education standards documents from the USA, Korea and Taiwan: Focusing on disciplinary aims, values and practices. *Science & Education, 29*(4), 899–927.

Pleasants, J., & Olson, J. K. (2019). What is engineering? Elaborating the nature of engineering for K-12 education. *Science Education, 103*(1), 145–166.

Pleasants, J., Clough, M. P., Olson, J. K., & Miller, G. (2019). Fundamental issues regarding the nature of technology. *Science & Education, 28*(3–5), 561–597.

Poel, I. (2015). Values in engineering and technology. In W. J. Gonzalez (Ed.), *New perspectives on technology, values and ethics* (pp. 29–46). Springer.

Purzer, S., Quintana-Cifuentes, J., & Menekse, M. (2022). The honeycomb of engineering framework: Philosophy of engineering guiding precollege engineering education. *Journal of Engineering Education, 111,* 19–39.

Violante, M. G., & Vezzetti, E. (2017). Guidelines to design engineering education in the twenty-first century for supporting innovative product development. *European Journal of Engineering Education, 42*(6), 1344–1364.