Understanding of the Nature of Engineering: Examining the Gap Between Engineering Experts and Pre-service Teachers

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***Abstract*—In today's technology-driven world, marked by innovations such as generative AI, it is essential to prepare pre-service teachers (PSTs) with the knowledge and skills to address new challenges in science education. PSTs with a background in science and engineering are potential change agents for shaping and promoting engineering literacy. However, even teachers with backgrounds in science and engineering often lack a deep understanding of the fundamental nature of engineering. Moreover, there is a lack of training programs to support school-level engineering education. Hence, the aim of the study was to examine gaps in the understanding of the Nature of Engineering (NOE) between engineering education experts and PSTs to provide cognitive-epistemic and social-institutional heuristics for bridging these gaps. The research utilizes the Family Resemblance Approach (FRA) as a theoretical and methodological framework to investigating the NOE understanding as well as proposing heuristics for best practices. The study used the integrated dual- analytic approach, in which data were collected via semi- structured interviews among 17 engineering education experts and a survey among 43 PSTs. The findings revealed that while the experts conceptualize the NOE as a system of interacting components, consisting of a wide range of cognitive-epistemic and social-institutional aspects, the PSTs exhibited a narrower stance. The experts in engineering education emphasized social values, ethos, political power structures, and financial systems that impact the work of engineers. In contrast, the PSTs primarily mentioned engineering aims, knowledge and methods, while largely overlooking the social-institutional aspects. The implications of this study are significant for sustaining educational excellence in pre-college engineering education. By exposing PSTs to FRA- based interventions and emphasizing the interdisciplinary, socially embedded nature of engineering, teacher preparation programs can better equip future educators to integrate engineering concepts into their classrooms. By focusing on both cognitive-epistemic and social-institutional dimensions of NOE, this research provides valuable insights into how PSTs can be supported in developing a more comprehensive understanding of engineering. In the era of Generative AI and 21st-century skills, this study contributes to the ongoing dialogue on preparing educators to equip future generations with the competencies needed to become informed citizens capable of addressing the challenges of an evolving technological society.**

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I. Introduction

The increasing interdisciplinarity of scientific fields underscores the importance of integrating engineering concepts into the science curriculum [1-4], with the intent to promote engineering literacy from an early stage. Such integration holds the potential to deepen students' understanding of scientific principles by encouraging them to apply concepts in authentic contexts, thereby fostering a richer grasp of the technological world around them [5-6]. Introducing engineering concepts in pre-college education may also inspire students to pursue engineering careers, helping to mitigate the ongoing shortage of engineering talent. Core engineering principles—including objectivity, novelty, and accuracy—are deeply connected to addressing complex, real-world challenges that require solutions rooted in environmental responsibility, ethics, and social sustainability. Yet, engineering's complexity, often necessitating advanced scientific knowledge and high-level mathematical skills, presents notable challenges for both teachers and students [7-8]. To facilitate authentic engineering learning experiences, pre-service teachers (PSTs) need a comprehensive instructional perspective on the nature of engineering (NOE). However, existing literature highlights the complexity of NOE conceptualization and the lack of consensus on effective approaches to foster PSTs' understanding of it [2, 8-10]. This challenge is further compounded by the shortage of schoolteachers with an engineering background, which hinders the effective communication of complex engineering concepts [3, 8, 11], as well as the limited availability of professional development programs designed to address this gap [2, 12-13].

PTSs, even those with a scientific background, lack specialized expertise in engineering education. As novices in this field, they need professional development to progress toward expert status. Discussion about expertise and gaps in knowledge between experts and novices has a long-standing history across various domains. Researchers identified disparities in how experts construct knowledge, pointing to richer and better organized mental structures, [e.g., 14-15]. They also point to deeper conceptual understanding used by experts when approaching complex problem-solving [16]. Experts organize their knowledge around fundamental conceptual principles; whereas novices require explicit instruction and examples [14]. Specifically in education, expert understanding is considered the “goal state”, while novice understanding is the “initial state” of the learning process. To close these gaps, it is essential to design instructional interventions that can elevate novices to expert levels of understanding [15, 17-18]. In engineering education, progressing the understanding level of the NOE along the novice-to-expert continuum remains an area not yet fully explored in the literature.

This study addresses this gap by using the Family Resemblance Approach (FRA) to examine the conceptualization of NOE of experts compared to novices. Emerging research suggests that the FRA offers a promising framework to cultivate an inclusive understanding of both the cognitive-epistemic and social- institutional dimensions of NOE [2, 19], drawing upon recent studies of FRA to the Nature of Science (NOS) [20-21]. This paper explores the potential of adapting the FRA framework to conceptualize engineering as a diverse yet interconnected “family” of disciplines, each with unique approaches and shared principles. It further examines whether this approach could offer a potential method, yet to be tested, for bridging gaps in understanding the NOE in pre-service teacher education.

Hence, the aim of our study was to examine gaps in the understanding of the NOE between engineering education experts and PSTs to provide cognitive-epistemic and social-institutional heuristics for bridging these gaps. The research utilizes the FRA as both a theoretical and methodological framework.

II. Family Resemblance Approach For The Nature of Engineering

Despite the emphasis on engineering practices within national and international standards and the positive outcomes demonstrated in recent studies [e.g., 6, 11], the integration of engineering concepts within science curriculum remains limited, with inconsistent application in classroom settings [12]. Consequently, many students complete their K-12 education with minimal or no exposure to engineering education [8, 11]. This lack of exposure can be attributed to several factors, including a shortage of teachers with engineering backgrounds [11], limited availability of engineering-focused training programs for in-service and pre-service teachers [3, 12], and the inherently complex nature of engineering, which requires advanced knowledge in science and mathematics [7-8].

In this study, the FRA was utilized for its unique capacity to incorporate domain-general and domain-specific features, making it particularly useful for examining how engineering education is conceptualized and understood [2]. The FRA framework offers the potential for conceptualizing the NOE by clarifying the distinct and interconnected aspects of the engineering field. Although interest in defining the NOE has grown, efforts to develop a standardized taxonomy remain in the early stages [2, 19]. Unlike the extensive literature on the Nature of Science (NOS), research on the NOE is still limited. This gap has led researchers to call for a clearer conceptualization of NOE within pre-college education, recognizing that engineering literacy is crucial for informed participation in modern society [3, 11].

The study utilized the FRA as a theoretical lens for framing the NOE as a two-dimensional system. The first dimension is the cognitive-epistemic, which includes four categories; the second dimension is the social-institutional one, which includes seven categories divided into two groups – core categories and broader categories, as shown in Table 1. The core categories refer to the engineers’ social norms and their work in professional communities; while the broader categories refer to the larger society, in which engineering, like other organized human activity, is being practiced.

III. Methodology

The research involved 17 experts in engineering education and 43 pre-service science teachers (PSTs). Engineering education experts were recruited through purposeful sampling [22], beginning with distinguished engineering professors who then recommended additional qualified experts within their professional networks. To capture perspectives across various engineering disciplines, the sample included a diverse group of engineering professors, curriculum designers specializing in science and engineering, veteran teachers with an engineering background, and practicing engineers with teaching experience. Data from the experts were collected via semi-structured interviews, which included questions referring to the conceptualization of the NOE. For example: What comes to mind when you hear the term ‘nature of engineering’? or how should the ‘nature of engineering’ be defined? The PSTs were recruited from a teacher certification program they participated in. Less than half (43%) hold a science background (e.g., chemistry, biology, physics), while the rest (57%) hold an engineering background (e.g., civil engineering, mechanical engineering, electrical engineering). Data from the PSTs were collected via a short survey with open questions, similar to those presented to the experts.

TABLE I. FRA Domains and Categories

Cognitive-Epistemic	**Social-Institutional**	
	Core	**Broad**

(1) Aims & values	(5) Ethos	(9) Social organizations
(2) Practices	(6) Professional activities	(10) Political power structures
(3) Methods	(7) Social dissemination	(11) Financial systems
(4) Knowledge	(8) Social values	

The study used an integrated dual-analytic approach [23], in which data were analyzed both qualitatively and quantitatively to provide complementary insights. Responses from engineering education experts and PSTs were analyzed by two educational researchers following a thematic analysis approach [22, 24]. The analysis proceeded through the following steps: First, all participant responses were compiled into a cohesive document. This document was thoroughly reviewed, with text segments relevant to NOE conceptualization and heuristics for a comprehensive understanding of engineering highlighted. Using a deductive approach [24], these highlighted segments were then categorized according to predefined classifications based on the FRA framework [25]. Patterns within the data were examined to identify recurring themes, and responses were numerically coded to align with the appropriate FRA categories. The responses of experts and PSTs were compared within the FRA categories, allowing for the identification of understanding gaps. These gaps highlighted specific cognitive-epistemic and social-institutional heuristics that could support bridging the differences in understanding.

IV. Results

Data analysis revealed that the experts in engineering education conceptualize the NOE as a system of interacting components consisting of cognitive-epistemic aspects, mainly *engineering practices* and *knowledge*, as well as social-institutional aspects, mainly *social values*, *ethos*, *political power structures*, and *financial systems*. The *practices* category, which is part of the cognitive-epistemic dimension, was described by the experts as a set of skills required for designing solutions in the engineering process. As for the social-institutional dimension, the category of *social values* was referenced by the majority of experts, with *respect for the environment* and *ethical considerations* as major points for the engineer to consider. *Sustainability* was also expressed through the *ethos* category, with goals of well-being, prosperity, planet health, and equality. Both *political power structures* and *financial systems* were regarded by experts as an interplay of evaluation, analysis of alternatives and cost-benefit analysis as part of the engineer's work. Table 2. provides selected examples of excerpts from experts and PSTs to some of the categories of the FRA to NOE framework. Short definitions for the presented categories are also included.

To identify conceptualization gaps in PSTs' understanding of the NOE compared with experts, we conducted an analysis of their responses and frequency counts of the referenced FRA categories. While all eleven FRA categories were referenced by the experts, PSTs referred to nine categories, omitting *ethos* and *professional activities.* Moreover, most of the PSTs focused on cognitive-epistemic aspects of engineering, with a high percentage of participants referring to engineering *aims & values*. Only 16% of the PTSs referred to social-institutional aspects of the work of engineers. In contrast, the engineering education experts covered more aspects of the NOE while emphasizing *social values*, *ethos*, *political power structures*, and *financial systems* that both influence and are influenced by the work of engineers. Figure 1 depicts frequency counts of the FRA categories referenced by experts compared to PSTs.

Looking at the broader aspect of the social-institutional dimension, the three categories of *social organizations*, *political structures*, and *financial systems* were mentioned by only 6% of the PSTs compared to 14% of the experts. A chi-square test of independence showed a significant association between participant (PSTs vs. experts) and the FRA referenced, $\chi^2(5, N=60) = 13.53$, $p < .02$. Even in the instances that PSTs did reference broader social-institutional aspects, their examples were relatively narrow in scope. In particular, they highlighted specific details without illustrating how various considerations are interconnected within the broader context. In contrast, the engineering education experts asserted a wider epistemology, with interwoven considerations characterizing the NOE. For example, while the PSTs mentioned project- specific budget and cost control considerations, the engineering education experts allude to industry-wide economic impacts and financial policies affecting engineering decision making.

V. Summary and Future Research

A comprehensive, unified perspective of the nature of engineering (NOE) is crucial in our modern technology-based society for fostering informed and engaged citizenship. As generative AI becomes more prevalent, embedding engineering values, principles, and ethical commitments into problem- solving is essential to ensure societal benefit in an effective, equitable, and non-harmful way. Moreover, understanding the interplay between engineering and society is essential for responsibly addressing pressing global trends with the needed knowledge, skills, attitudes, and values. However, the integration of engineering concepts into pre-college education is still limited. This study identifies gaps in pre-service teachers' (PSTs') understanding of the NOE compared to engineering experts' conceptualization and emphasizes the need for equipping PSTs with a more holistic understanding. It underlines cognitive-epistemic and social-institutional heuristics that may support PSTs to achieve expert-like understating of the NOE. In trying to offer a fully defined and instructive approach to the NOE, this study utilizes the Family Resemblance Approach (FRA) to conceptualize engineering as

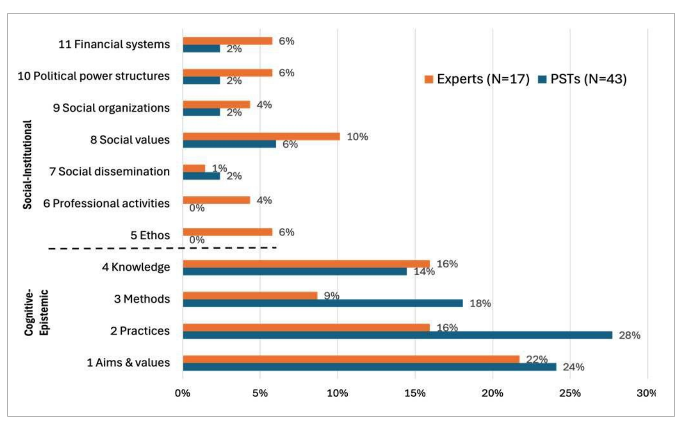

Fig. 1. The percentage of experts vs. PSTs per FRA to NOE category

TABLE II. EXCERPTS FROM ENGINEERING EDUCATION EXPERTS AND PSTS FOR THE FRA TO NOE CATEGORIES

Category	Definition	Example
Aims & values	Improving or creating new artifacts based on human needs, seeking novelty, objectivity and commercial value.	**Expert:** *"Engineering is a profession dedicated to addressing societal needs and delivering solutions that minimize harm"* (A.B., engineering professor and curriculum designer). **PST:** *"Engineering is about using machines and technology to benefit man… like an intelligent robot that can make coffee"* (A.Y., MSc in industrial engineering).
Practices	Defining human-related problems, developing and using engineering models, and designing solutions.	**Expert:** "*In engineering, one needs 21st century skills, such as the ability to work in a team, be a self-regulated learner, think creatively, and define and solve problems*" (A.A., engineering curriculum designer). **PST:** *"Engineering includes different specializations, and in the end provides solutions to a problem"* (A.S., MSc in physics and electrical engineering).
Ethos	Seeking reliable outcomes regarding the safety of users and reducing financial and health risks.	**Expert:** "*…the engineer must consider value-related factors, such as whether the development and the resulting improvement in quality of life align with sustainable development goals, like those established by the UN*" (D.B., engineering curriculum designer). *"For example, an autonomous car – what are the ethical considerations of this development"* (R.E., engineering professor). **PST:** no references
Social values	Respect for the environment, intellectual freedom, and social considerations that guide engineers' designs and decisions.	**Expert:** "*Engineers should consider environmentally sustainable solutions while also addressing potential ethical concerns. They need to perform a life cycle assessment and look beyond the solution itself… this is the challenge of the modern engineer. For example, the environmental implications of electric cars – what are this development and how does this impact human behavior*" (A.B., engineering professor). **PST:** *"Human and environmental needs drive the world of engineering, including health and medical needs, nutrition, welfare, security, and other social needs"* (K.R., BSc in science).
Political power structures	The work of engineers can be impacted by the decisions made in politics; engineering projects and products can influence political power structures.	**Expert:** "*In a public health project, you need to consider policy factors, such as who establishes the policies, sets national priorities, and how policymakers and politicians play a role in the process*" (O.Y., engineering professor). **PST:** *"Technology is multidisciplinary and involves economic, social, and constitutional considerations in solving technological problems. For example, satellites are used for military purposes"* (B.B., BSc in food engineering).
Financial systems	Engineers consider financial and economic factors (e.g., interest rates, inflation, financial stability) when designing artifacts.	**Expert:** "*Cost-benefit analysis is essential in engineering… you also must be able to pitch your idea and present it to investors, whether your client is a government or a for-profit company*" (A.W., teacher with an engineering background and curriculum designer). **PST:** *"Engineering is greatly influenced and driven mainly by the desire for economic gain, it is a key consideration in engineering"* (A.M., BSc in biology).

a diverse yet interconnected "family" of disciplines. It suggests designing teacher development programs that focus on the FRA's various dimensions and thus introduce a holistic conceptualization of the NOE.

In this study, we point to the need for designing and implementing explicit-reflective instruction and a self-directed learning process supported by active methods of teaching and learning. In particular, we suggest that future research and learning activities integrate problem-based learning, case studies, collaborative exercises, and analogies to facilitate discussion on the 'nature of engineering' and foster engineering literacy. These instructional methods were chosen as they enrich the learning experience by making it more relevant, practical, and engaging. Specifically in STEM education and in particular in engineering, where a self-directed learning process in teams is often implemented, active methods of teaching and learning have been shown to cultivate skills required for the 21st century [26]. These forms of teaching and learning thus result in a well-rounded, real-world understanding, advancing learners towards the goal of engineering literacy. The instruction should illustrate science and engineering as a family of commonalities and differences, focusing on the cognitive- epistemic and social-institutional dimensions of engineering. Additionally, we suggest reinforcing the instruction and learning activities with visual representations that align with and are informed by the FRA framework.

Heuristics for Bridging the Gaps in Understanding

The identified gaps in NOE understanding between the experts and the PSTs highlighted cognitive-epistemic and social-institutional heuristics that could support bridging these differences. Heuristics of the FRA framework facilitate the design of lesson plans that can support the gradual construction of NOE understanding to that of an expert in the field of engineering education. One such example is the Benzene Ring heuristic, which presents a holistic, memorable representation of the epistemic, cognitive, and social-institutional components of scientific practices [25]. Figure 2 is an example of a lesson plan that was developed to discuss different engineering fields. The lesson demonstrates that engineering is a dynamic and creative process, utilizing multiple design methods to address complex human challenges from diverse perspectives.

Enactment of the teacher development program will enable explicit and reflective opportunities to discuss NOE from a more nuanced and holistic point of view. The study suggests that providing PSTs with a comprehensive, unified approach to NOE guided by the FRA framework may result in a broader perspective. PSTs as future change agents can inspire students to embrace a shared responsibility in addressing social and global challenges. The methodological contribution of the current study lies in framing the NOE via the FRA. Future studies may build on this methodology and further examine how the trajectory of NOE understanding evolves through targeted professional development activities.

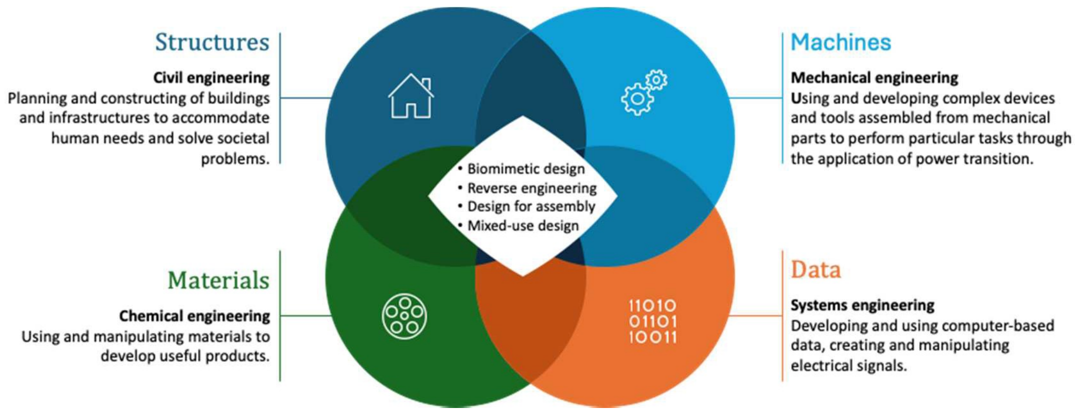

Fig. 2. A lesson plan discussing engineering fields and methods.

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