Fundamental Research: A Framework for Socially Transformative Engineering through Conscientious Design (Other)

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Abstract

Engineering education holds a profound potential to promote youth's understanding and engagement in environmental sustainability, social justice, and decision-making in an AI-enabled future. However, the traditional approach to defining engineering that has guided engineering practices is insufficient because it fails to embrace these realities. Therefore, the need for a new framework that reflects these realities is overwhelming. This paper introduces a new theoretical framework called socially transformative engineering that not only captures these missing elements but also values and incorporates the diverse perspectives and experiences of students. In particular, this framework draws upon the legitimation code theory and justice-centered pedagogies and builds on three tenets (reasoning fluency, multicultural ingenuity, and ethical integrity). Further, this framework argues that conscientious negotiation of risks and benefits for the betterment and transformation of societies is underpinned by four reasoning quadrants (experiential reasoning, trade-offs reasoning, first-principles reasoning, and future reasoning), fluently examined through the core practice of multicultural ingenuity and ethical integrity. This paper details the theoretical foundations of the socially transformative framework and provides examples of its pedagogical translations to guide pedagogy practices.

Introduction

Engineering, as commonly understood, is the practical application of scientific and mathematical principles [1], the creation of new products [2], and the procedures involved in effecting the best changes in a poorly understood situation within the available resources [3]. It is no surprise that these definitions, focusing on applications, processes, and products, are dominant in efforts to infuse engineering into K-12 science education. The following quote from Next Generation Science Standards [4], further justifies this claim:

> "*It is important for students to explore the practical use of science, given that a singular focus on the core ideas of the disciplines would tend to shortchange the importance of applications... engineering and technology provide a context in which students can test their own developing scientific knowledge and apply it to practical problems; doing so enhances their understanding of science—and, for many, their interest in science...*" (NRC, 2012, p.12).

According to a study by Pawley [5], engineering professors also use similar descriptions of engineering, such as applied science and math, making things, and problem-solving. However, viewing engineering as an applied science is too narrow, while viewing engineering as problem-solving is too broad. First, engineering is multifaceted and involves a diverse array of inquiries, such as optimization and engineering science [6]. Second, engineering practice requires knowledge and responsibilities of science and mathematics, as well as other disciplines, such as sociology, ethics, and business [7]. More importantly, it is not clear how these definitions serve engineering's transformative mission of supporting environmental sustainability, social justice, and decision-making in an AI-enabled future.

Hence, it is important to examine our definitions so they can effectively guide our design practices. How would we approach engineering in the next century if we uphold the conventional notion of engineering as the application of science and mathematics to devise processes aimed at increasing efficiency and productivity? How would next-generation engineers approach design if engineering education persists in emphasizing the optimum utilization of natural resources to serve human endeavors? It is very unlikely that practices based on these definitions would help create a future where we achieve environmental sustainability and a just society.

Socially transformative engineering starts by examining our definitions and practices with a vision for how they influence the future. Our proposed framework aims to integrate engineering reasoning necessary for the future by engaging in conscientious negotiation of risks and benefits for the betterment and transformation of societies at the intersection of people, technological systems, the environment, and natural resources.

Why A New Framework?

K-12 engineering education has received a renewed importance in the U.S. since many U.S. states adopted the Next Generation Science Strands (NGSS) [8]. However, NGSS has also been critiqued for not tapping on the potential of engineering for addressing issues of social justice [9]. In recent years, engineering educators have developed pedagogical frameworks that have effectively been used to promote social justice and cultural assets in engineering education [10], [11]. These frameworks have provided specific pedagogical strategies on ways teachers and curriculum developers can promote equity, inclusion, and students' assets in the classroom. Others have highlighted the historical, ethical, and social dimensions of engineering education [12] such as the importance of multicultural ways of knowing for environmental sustainability and social justice [13], [14].

In the design world, there are also well-known frameworks, such as user-centered design [15], which highlights the need to gather user input at each stage of design. We provide a complementary framework that encompasses natural resources, expanding the care of users to create sustainable design solutions. Hence, user satisfaction is not simply reserved for the immediate users of design but extended to future generations.

With a new framework, we build on prior models by highlighting elements of ethics and multicultural perspectives, while emphasizing futures thinking and reasoning fluency. Termed socially transformative engineering, this approach situates youth as agents in designing sociotechnical infrastructures that require ethical, technical, scientific, and human judgment and provides a framework for achieving transformation towards a just and sustainable future. Such thinking is essential, especially as we prepare for a future led by AI-enabled technologies. Thus, our vision is for future generations who can make decisions conscientiously and design systems with ethical integrity and multicultural ingenuity.

Legitimation Code Theory and its Applications in Engineering

The foundations of reasoning are inherent within the disciplinary knowledge, discourse, and practices as expressed by Maton's [16] legitimation code theory (LCT). Given the emphasis on disciplinary discourse, Maton's theory articulates the critical role of semantic waves of disciplinary discourse across what he calls semantic density (SD) and semantic gravity (SG). Where semantic density (SD) represents a condensation of meaning, ranging from isolated disciplinary discourse to condensed multidisciplinary discourse. Semantic gravity (SG) represents context dependency, with strong SG representing practical context-dependent explanations and weak SG representing theoretical and de-contextualized explanations. The applications of LCT to engineering education have advanced our understanding of design reasoning [17].

As Wolmarans [17] applies the semantic density concept to engineering design, she distinguishes complexity as multi-disciplinary knowledge. Wolmarans defines semantic gravity across theoretical knowledge and practical knowledge in engineering. In our framework, we integrated these two key elements of disciplinary discourse (semantic gravity and semantic density). When these two elements intersect, the resulting is a visualization [18], labeled the Design Reasoning Quadrants. At the intersection of the axes of semantic gravity and semantic density, four design reasoning quadrants emerge: experiential, first-principles, trade-offs, and future reasoning (See Figure 1). Thus, this framework builds on multicultural ingenuity, ethical integrity, and reasoning fluency.

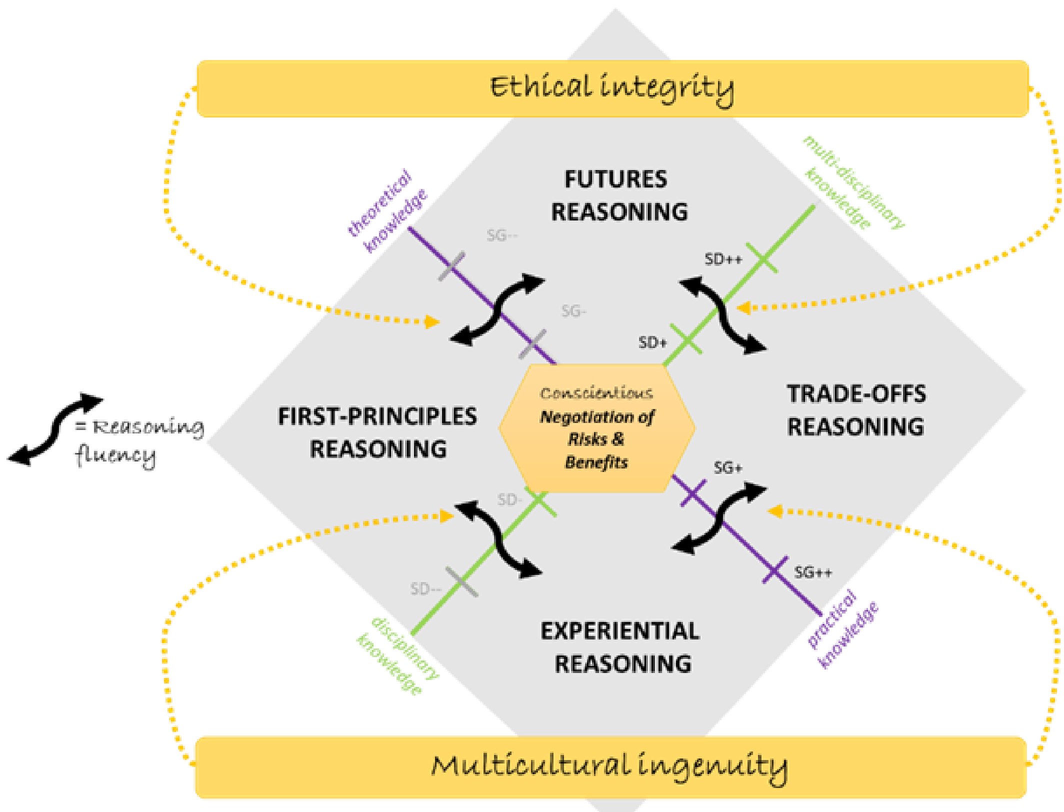

Figure 1. *Framework for Socially Transformative Engineering through conscientious design (SG: semantic gravity; SD: semantic density)*

Three Tenets and Theoretical Foundations of Socially Transformative Engineering

The *Socially Transformative Engineering* framework has three tenets: reasoning fluency, multicultural ingenuity, and ethical integrity. These tenets are developed through the purposeful integration of the legitimation code theory [16], justice-based science education pedagogies [12] as well as research on the philosophy of engineering and future-thinking literacy [19], [20]. .

(1) **Reasoning fluency**: Socially transformative engineering requires fluency across four different quadrants of reasoning: 1) understanding of the current situation, facilitated by information gathering and the decision-makers prior experiences and multicultural perspectives (experiential reasoning); 2) understanding disciplinary core ideas that cross multiple disciplines such as science, mathematics, civics, ethics, and economics (first-principles reasoning); 3) recognizing competing requirements, trade-offs, and assumptions (trade-offs reasoning); and 4) contemplating potential futures if a design is deployed along with plausible and unintended risks and benefits (futures reasoning). The conscientious negotiation of risks and benefits stimulates fluency across reasoning quadrants [28]. While experiential reasoning is where many students are comfortable with, our prior studies uncovered limited evidence of fluency into futures reasoning [18].

(2) **Multicultural ingenuity**: *Multicultural ingenuity* connects reasoning from experiential reasoning to other quadrants of reasoning but also serves as an interesting catalyst [21]. In alignment with the justice-centered science pedagogies, students' agency is recognized, and culturally rich ways of being and knowing are valued [22], [23] [24]. Engineering education has its challenges because the traditional practices of engineering have contributed to manifestations of mono-culturalism in areas such as environment and public health [12], [25]. Yet, culturally rich ways of knowing are critical to problem scoping and generating just and sustainable solutions.

(3) **Ethical integrity**: Morally committed practices require careful examination of benefits and burdens, contemplating multiple futures, and careful examinations of trade-offs. For engineering to be the solution, it must serve the betterment of societies not for immediate but across the life span of a technology with the assessment of impacts on people and natural resources. Such reasoning is necessary as we are designing systems with AI capabilities. As stated by [26], cultivating the habit of ethical judgment is important in engineering, and design education should promote reflexive and reflective practitioners. Engineering education can then support social responsibility and promote learners as active change agents for a better world [27].

When designing, experiential observations are typically where learners start to reason through - this is where they initially and naturally gravitate towards. Hence, experiential reasoning is the entry point towards more complex ways of thinking. *Multi-cultural ingenuity*, as illustrated in Figure 1, connects experiential reasoning to other forms of reasoning. In alignment with the legitimation code theory [16], the experiential reasoning quadrant reflects strong semantic gravity where discourse is dependent on context, with highly descriptive explanations based on lived experiences. While experiential reasoning does not directly translate into futures reasoning, it is the necessary foundation for building up first-principles and trade-offs reasoning, which then promotes futures reasoning. However, futures reasoning is necessary for sustainable decision-making, but least evident in pre-college engineering education efforts. In addition, ethical integrity is affiliated with futures reasoning informed by first-principles and trade-offs reasoning. In summary, a critical contribution of the Socially Transformative Engineering Pedagogy is engaging learners in different modes of reasoning so they can achieve their full potential for conscientious decision-making.

Pedagogical Translation of the Socially Transformative Engineering Framework

Integrating a new framework with an emphasis on engineering reasoning fluency while integrating social and ethical perspectives can be daunting. Therefore, we present an illustrative lesson inspired by a curriculum developed by Sung and colleagues [29]. In this lesson, engineering is not the central focus, but engineers are situated as part of a legal case. As part of the legal case, two engineers are the expert witnesses, one representing the defendant and the other one representing the plaintiff (See Figure 2). In this lesson, students are provided with opportunities to participate in decision-making processes with the ability to *influence* the outcomes of a case adopted from a real legal case [30], [31]. Students used Aladdin, a free and open-access computer-aided design software, to simulate and calculate energy generation in kWh when trees are trimmed or removed (See Figure 3).

Legal Dispute between Neighbors over Solar Panels

This 10-day lesson is anchored on a real legal dispute involving two neighbors. The plaintiff installed solar panels on the porch roof of their house with a permit. Their neighbor, the defendant, planted eight redwood trees on their property next to the defendant's property without a permit. The panels face south to receive maximum solar exposure, but they also face the defendant's redwood trees [32], [33].

Figure 2. Solar panels vs. trees [32]

A lesson designed to promote socially transformative engineering starts by first eliciting and engaging students' experiential reasoning. This is because learners naturally gravitate towards experiential observations as a comfortable starting point. This orientation also offers an opportunity to engage students' multidisciplinary ways of knowing. In the sample lesson, to elicit experiential reasoning, students are asked to share their impressions, thoughts, and feelings about the situation after they have been introduced to the legal dispute.

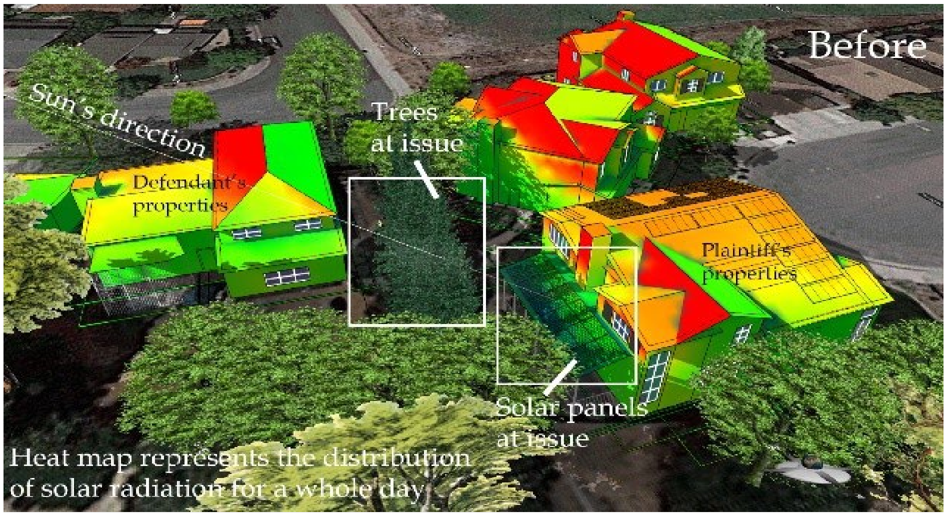

Figure 3. Aladdin CAD and simulation of the buildings [32]

As summarized in Table 1, the lesson is distributed across ten days and four stages. In the first stage (day 1), students practice experiential reasoning by sharing initial impressions, past experiences, and feelings after reading the legal case. In the second stage (days 2-4), students take roles and use first-principles reasoning to gather evidence by studying scientific principles such as solar radiation and the impact of shading (e.g., due to tree growth) on solar insolation. During the third stage (days 5-8), students present the evidence they gathered with tables and figures. These data provide an opportunity to practice trade-offs reasoning and weigh risks and benefits in support of a position (the defendant or plaintiff). Stage four (days 9-10) is the post-mock trial discussion, during which students practice future reasoning by imagining near and far future implications on people and the environment if a similar court decision was made in their own state.

Eliciting Conscientious Design Reasoning

Discourse is essential in facilitating student learning and reasoning when implementing the socially transformative engineering framework. In particular, design coaching, enriched with reasoning eliciting questions, can help educators understand students' design decisions, positions, and arguments. Table 2 presents examples of ways educators can elicit different forms of reasoning (experiential, first principles, trade-off, and future) and promote fluency across reasoning quadrants.

There is no hierarchy across the reasoning quadrants as the aim is to achieve fluency across quadrants. Typically, experiential reasoning questions lead the design coaching conversations. However, questions do not need to be asked in a static order. Generally, the experiential reasoning questions are followed by either first principles or trade-offs questions and then futures reasoning. However, it is important to approach the coaching session with the purpose of understanding students' decisions (and not with the purpose of assessing or judging) to promote student agency, listen to their responses, and help the students delve into deeper reasoning.

Table 1ey activities of the ten-day lesson and reasoning elicited in alignment with the framework

	Activities	Reasoning Elicited
Day 1	The student read **news about a real legal case** involving a neighbor dispute about trees blocking solar panels.	Eliciting EXPERIENTIAL reasoning through multi-cultural ingenuity • Share your first impression and feelings about the case/project. • Does the neighborhood look familiar? • Who seems to have a better case?
Day 2-4	Students take roles (forensic engineer, judge, jury, lawyer, etc.) and **gather evidence** by learning daily scientific concepts related to seasonal variations in solar energy, azimuth & tilt angles, photosynthesis, and carbon sequestration, product life cycles, civic rights, and state laws.	Eliciting FIRST-PRINCIPLES reasoning to inform conscientious negotiation of risks and benefits • What evidence do you recommend that the defendant gather? • What evidence do you recommend that the plaintiff gather?
Day 5-8	A mock trial is when evidence is presented with tables, figures, and statements establishing risks and benefits, making a case in support of the plaintiff or defendant. Jury deliberation is when **evidence is examined and conscientiously negotiated** to reach a consensus on a decision.	Eliciting TRADE-OFFS reasoning through conscientious negotiation of risks and benefits • What would be the burdens if the plaintiff wins the case? • What would be the burdens if the defendant wins the case? • What are the advantages and disadvantages of laws that protect solar panel owners?
Day 9-10	Students imagine **multiple futures** depending on which side wins the case. For their state legislature, students work in teams to write a bill that 10 years from today, will continue to promote environmental benefits and reduce burdens on citizens	Eliciting FUTURES Reasoning through ethical integrity • What would be the impact in 5 years if the plaintiff wins the case (e.g., trees are trimmed or removed)? • What will be the impact in 5 years if the defendant wins the case (e.g., solar panels are removed or moved)? • What would be the impact if the same laws were implemented in your state, your neighborhood?

Conclusion

The socially transformative engineering through conscientious design framework aims to elevate the potential of engineering education to empower learners, support environmental sustainability, and promote social justice. Contemporary challenges require an engineering education that goes beyond applying science and mathematics to solve problems and rather embraces social justice and environmental sustainability. The goal of this paper is to introduce a theoretical framework that incorporates experiential, first principles, trade-offs, and futures reasonings with ethical integrity and multicultural ingenuity in support of socially transformative engineering pedagogy. The framework emphasizes the need to promote reasoning fluency across four reasoning quadrants (experiential reasoning, trade-offs reasoning, first-principles reasoning, and futures reasoning). This fluency is facilitated through the core practice of conscientious negotiation of design risks and benefits and amplified through multicultural ingenuity and ethical integrity. It is hoped that the *Socially Transformative Engineering* framework will cast a ray of light into viewing engineering with a wider social and ethical lens, inspire futures reasoning fluency in learners, and help educators navigate the intricacies of educating the next generations to design conscientiously.

Table 2 Contextualizing the Reasoning Quadrant

Definition	Eliciting Reasoning through Design Coaching	Sample Response
Experiential reasoning refers to ways of knowing and being developed through past experiences as well as recent knowledge gained through experiments and information gathering [18], [28].	**Experiential reasoning** • *What are your first impressions and feelings about this case/project?* • *Are there ways this case relates to your neighborhood?*	***I was thinking about the houses in my neighborhood****. There are a lot of trees in my neighborhood, and some have fencing. I wondered if we'd have a problem if our neighbor installed solar panels.*
The first principles are disciplinary core ideas such as scientific and mathematical concepts but also principles from other disciplines such as civics literacy, ethics principles, economics, etc. [18], [28].	**First-principles reasoning** • *What evidence do you advise the defendant to gather?* • *[Possible follow-up: What evidence do you advise the plaintiff to gather?]*	So, basically, ***how many kwh*** would be generated with and without trees by the solar panels on the roof. I would first check for summer because ***winter would be different***.
Trade-offs reasoning is understanding multiple design requirements that need to be explored and weighted when designing. Trade-offs include weighing advantages and disadvantages with respect to design criteria and constraints [18], [28].	**Trade-offs reasoning** • *What would be the burdens if the plaintiff wins the case?* • *[Possible follow-up: What would be the burdens if the defendant wins the case?* • *What are the advantages and disadvantages of the law for different people?*	Cutting the trees will result in less shading on the ***solar panels. It could maximize the energy…***
Futures reasoning involves imagining a situation in the future and contemplating what might happen if the context of the project or a feature of their design changes [18], [28].	**Futures reasoning** • *What would be the impact in 5 years if the plaintiff wins the case?* • *What would be the impact if the defendant wins the case?* • *What would be the impact if the same laws were implemented in your state?*	If no tree is allowed to grow taller than a single-story house... that would be ***devastating in the long run***. Maybe solar farms are the future, rather than household panels. Or maybe buildings must be multi-story for solar panels.

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