Establishing a Content Taxonomy for the Coherent Study of Engineering in P-12 Schools

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Abstract
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Keywords
P-12 engineering education, content taxonomy, engineering literacy

Document Type
Research Article

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Establishing a Content Taxonomy for the Coherent Study of Engineering in P-12 Schools

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Abstract

Engineering education has increasingly become an area of interest at the P-12 level, yet attempts to align engineering knowledge, skills, and habits to existing elementary and secondary educational programming have been parochial in nature (e.g., for a specific context, grade, or initiative). Consequently, a need exists to establish a coherent P-12 content framework for engineering teaching and learning, which would serve as both an epistemological foundation for the subject and a guide for the design of developmentally appropriate educational standards, performance expectations, learning progressions, and assessments. A comprehensive framework for P-12 engineering education would include a compelling rationale and vision for the inclusion of engineering as a compulsory subject, content organization for the dimensions of engineering literacy, and a plan for the realization of this vision. The absence of such a framework could yield inconsistency in authentically educating students in engineering. In response, this study was conducted to establish a taxonomy of concepts related to both engineering knowledge and practices to support the development of a P-12 curricular framework. A modified Delphi method and a series of focus groups—which included teachers, professors, industry professionals, and other relevant stakeholders—were used to reach a consensus on engineering concepts deemed appropriate for secondary study. As a result, a content taxonomy for knowledge and practices appropriate for P-12 engineering emerged through multiple rounds of refinement. This article details the efforts to develop this taxonomy, and discusses how it can be used for standards creation, curriculum development, assessment of learning, and teacher preparation.

Keywords: P-12 engineering education, content taxonomy, engineering literacy

Introduction

Current initiatives in P-12 engineering education are encouraging: progress has been made to incorporate engineering into the Next Generation Science Standards (NGSS Lead States, 2013), programs such as Engineering is Elementary continue to expand, and the inclusion of engineering design has permeated all subject areas through integrated science, technology, engineering, and mathematics (STEM) education practices. Relatedly, calls have even been made for the creation of P-12 engineering educational standards (Carr, Bennett, & Strobel, 2012; Grubbs, Strimel, & Huffman, 2018). However, preceding such standards, and the corresponding development of curricula and formative or summative assessments of learning, is a coherent curricular framework that is developmentally sequenced for P-12 students. Supporting
this claim, a National Academy of Engineering (2017) report states that “one need is for a better understanding of what engineering content knowledge teachers need for different grade bands” (p. 15). In addition, the Building Capacity for Teaching Engineering in K-12 Education report (National Academies of Sciences, Engineering, & Medicine [NASEM], 2020) recommends research efforts to (1) describe the subject-matter and pedagogical content knowledge required for the high-quality teaching of engineering across grades and (2) document age-appropriate expectations and progressions of learning for K-12 engineering education. Without such a framework and clear vision, teachers may find the implementation of P-12 engineering education challenging and face difficulty in teaching in-depth and authentic practices of engineering.

To address this concern, the National Academy of Engineering (2017) recommends that content experts work with grade-level experts to develop a content taxonomy for P-12 engineering education. In response, the authors of this study initiated a collaborative community of experts to establish a content taxonomy capable of supporting a coherent framework for P-12 engineering teaching and learning. More specifically, the authors sought to provide an epistemological foundation for the study of engineering at the P-12 level by establishing a taxonomy of (1) concepts and (2) sub-concepts. This taxonomy would inform the development of age-appropriate progressions of learning to be implemented and tested in schools. This effort, and the focus of this article, involved research and developmental work to form the taxonomic structure and identify the appropriate concepts of engineering knowledge and practice. To do so, the authors followed the recommendations of the National Academy of Engineering (2010) and employed a modified Delphi method, as well as a series of focus groups involving teachers, professors, industry professionals, and other relevant stakeholders, to reach a consensus on the engineering concepts deemed appropriate for the secondary study of engineering. Through these efforts, the authors expected to provide information to answer the broader question of “If engineering becomes a compulsory subject in school to achieve engineering literacy for all students, what should teachers teach?” The lack of such information can continue to contribute to the unevenness, inconsistency, and inequity of engineering learning across the country (National Academy of Engineering & National Research Council, 2009). Therefore, the ultimate goal of this work is to ensure that every child is given the opportunity to think, learn, and act like an engineer.

Engineering in P-12 Education

The educational benefits of engaging P-12 students in engineering experiences continue to be promoted (Strimel, Bartholomew, Kim, & Cantu, 2018; Strimel, Bartholomew, Kim, & Zhang, 2018; Strimel, Grubbs, & Wells, 2016). However, minimal attempts in the United States have been made by the educational community to establish a deliberate and coherent study of engineering on a national level. Specifically, few efforts have been undertaken to identify developmentally appropriate content and practices for scaffolding the teaching of engineering at the P-12 level (National Academy of Engineering, 2017). As Reed (2018) stated, “engineering is well-defined at the postsecondary level but still evolving in P-12 education” (p. 19). While related educational standards in science education (Next Generations Science Standards) and technology education (Standards for Technological Literacy) have included engineering practices and content to facilitate learning experiences, there is still vast uncertainty as to how engineering should be intentionally taught in elementary and secondary schools. In addition, the science and technology education standards may provide a limited view of authentic engineering, specifically with concern to engineering content and competencies beyond design. This potential lack of authenticity may lead to a misrepresentation of what engineering is and is not. As discussed by the Executive Director of the American Society for Engineering Education, Norman Fortenberry (2018), knowledge of how to authentically teach engineering is intimately tied to the understanding of engineering as a discipline. However, there are currently no national content frameworks or learning progressions that aim to wholly define P-12 engineering as a stand-alone school subject and to explicitly guide the development of elementary, middle, and high school engineering education programs.

In 2009, Rodger Bybee, a renowned educator, researcher, and leader in science education, argued that the timing is right for the emergence of P-12 engineering education and the potential creation of engineering educational standards. However, the 2010 National Academy of Engineering’s Committee on Standards for K-12 Engineering Education decided to oppose the development of stand-alone standards at the time. The committee’s report highlighted multiple reasons, including schools’ relatively limited experience with K-12 engineering education, a lack of teachers qualified to deliver engineering instruction, and uncertainty over the impact of standards-based educational reforms on student learning. Instead, the committee recommended the integration of engineering content into current school curriculum as they believed it to be the quickest and least difficult way to begin exposing more K-12 students to engineering. However, following that report, many have supported the development of a true engineering content structure as P-12 engineering programs have become more widespread. For example, Pinelli and Haynie (2010) stated “it is imperative that engineering should be included in the K-12 school curriculum, both as a discipline and as a source of enrichment and context for teaching other subjects.” Subsequently, after their study of state standards in engineering across the United States, Carr et al. (2012) concluded that “now is the time to move forward in the formation of national standards based on the state standards identified in this study” (p. 539). Samuels and Seymour (2015)
emphasized the need for engineering coursework and called on the country’s engineering and educational communities to create a set of foundational concepts establishing engineering as a stand-alone topic in the nation’s schools. Strimel and Grubbs (2016) recommended a true focus on engineering as a core disciplinary subject. Then, in 2017, the National Academy of Engineering explicitly called for a better understanding of what engineering content knowledge teachers need for different grades. Lastly, the NASEM (2020) stressed the need to better support teachers preparing to teach engineering, as well as the importance of more formal accreditation guidelines to build the capacity to guide all students toward engineering literacy. It is evident that, over the last decade, support and efforts have increased to purposefully include engineering at the P-12 level.

In response to these various “calls to action,” there have been a few studies published that aimed toward identifying concepts, skills, and dispositions appropriate to P-12 engineering education. While some studies have focused on analyzing existing literature, others employed Delphi study approaches to help collect and build a consensus on experts’ opinions (National Academy of Engineering, 2010). For example, the National Academy of Engineering (2010) examined eight such studies and identified a total of 33 concepts, skills, and dispositions. These included design, engineering and society, constraints, communication, modeling, optimization, and analysis as big ideas in engineering at the P-12 level. While several of these studies involved the participation of both engineering educators and engineers, some lacked the contribution from a wider range of stakeholders, including K-12 teachers, policymakers, and school administrators. Further deficiencies included discussions on how to communicate the findings with key audiences and develop or implement learning materials—which is recommended by the National Academy of Engineering in their 2017 report titled Increasing the roles and significance of teachers in policymaking for K-12 engineering education. However, in 2014 Moore and colleagues did investigate how teachers and schools implement engineering and engineering design in their classrooms to create the first framework aimed toward providing a clear definition of what constitutes quality K-12 engineering education (Moore et al., 2014). The resulting framework presented key indicators for engineering education that have been demonstrated as useful to educators, predominately for evaluation purposes. While these findings have established a strong foundation for defining quality engineering education at the P-12 level, the key indicators can be improved by adding specificity of concepts. This could help to guide the organization of teachable and learnable engineering content over multiple grades at increasing levels of depth and sophistication (similar to Core Ideas for Science Education, A Framework for K-12 Science Education, 2012, p. 31). Accordingly, Moore and colleagues (2014) highlighted the need for continued research into how engineering is implemented at the P-12 level in order to further operationalize conceptions of engineering through the systematic definitions of each of their key indicators. Therefore, the authors posit that the development of a content taxonomy and progressions of learning for both engineering knowledge and practices, at a level of specificity which would allow schools and teachers to establish engineering learning pathways, is needed (National Academy of Engineering, 2017; NASEM, 2020). These efforts could help to extend the framework developed by Moore and colleagues (2014) and further define engineering literacy for all P-12 learners.

Engineering Literacy for All P-12 Learners

As the demand for high-quality engineers and related STEM professionals continues to increase (Change the Equation, 2016; Manpowergroup, 2015), achieving engineering literacy for all students should be at the forefront of any engineering education effort. The Bureau of Labor Statistics presented a projection in 2014 that the overall STEM employment would grow by 13% from 2012 to 2022—with occupations related to engineering and technology growing the fastest (Noonan, 2017). However, only a small portion of the nation’s youth are intentionally taught the concepts necessary to become engineering literate throughout their educational experiences. This is evidenced by the results of the first National Assessment of Educational Progress in Technology and Engineering Literacy (2016), which revealed that less than half of the nation’s eighth graders were on track to become engineering literate. Moreover, the results of this national assessment revealed that low-income and underserved minority students lagged the furthest behind in regard to engineering literacy, as they typically have the least exposure to core engineering fundamentals during school. Unfortunately, a student’s exposure to engineering seems to be completely left to chance based on their zip code, family’s income, and ethnicity, as only schools with abundant resources implement engineering programs as a superfluity rather than an obligation for all students (Change the Equation, 2016). This great disservice to the nation’s youth can be attributed to the lack of a defined sequence of learning progressions across and within each grade level, which would provide a roadmap toward achieving engineering literacy (Samuels & Seymour, 2015).

Engineering literacy can be viewed as closely related to technological literacy. However, the term “technological literacy” is often confused or misrepresented as “technology literacy” or even “computer literacy” by policymakers (Ollis & Pearson, 2006) and in school systems (Wicklein, 2006). With the rise of computer science education in P-12 schools, this distortion will likely continue to grow. Whereas technological literacy represents an understanding of the destination of human ingenuity (e.g., construction, manufacturing, medical, and transportation) and the human interactions with those
technologies (National Academy of Engineering & National Research Council, 2002), engineering literacy is concerned with the participation of inventors, innovators, makers, designers, and literate citizens in improving and interacting with the world’s systems, products, and services. These interactions require that an engineering-literate person become familiar with associated scientific, mathematical, and technical knowledge. As such, engineering literacy can be described as the confluence of content knowledge, habits, and practices merged with the ability to read, write, listen, speak, think critically, and perform in a way that is meaningful within the context of engineering (Lent, 2015; Wisconsin Department of Public Instruction, 2011). Equivalent to the idea of three-dimensional learning presented in the Next Generation Science Standards (NGSS Lead States, 2013), engineering literacy (see Figure 1) can be described as: (Dimension 1) engineering habits of mind, (Dimension 2) engineering practices, and (Dimension 3) engineering knowledge (National Academy of Engineering & National Research Council, 2006; Sneider & Rosen, 2009).

The three dimensions of engineering literacy include: (1) habits students should develop over time through repetition and conditioning; (2) practices in which students should become competent; and (3) knowledge that students should be able to recognize and potentially access, when appropriate, to inform their practices. These three dimensions help to determine how a pupil’s educational progress may be measured (see Figure 2). The habits of mind can be described as the traits or ways of thinking that influence how a person looks at the world or reacts to a challenge. These habits should become part of a student’s everyday thinking and allow them to routinely devise solutions to problems or improvements to current technologies or processes. Engineering knowledge can consist of the concepts that situate habits and practices in a conceptual domain, as well as enable sophistication in engineering practice. Engineering practices can be described as the skills and knowledge that enable a student to authentically act or behave like an engineer. While several efforts have been made to identify the big ideas of each engineering-literacy dimension, there is still a need to specify and reach a consensus on the concepts and corresponding age-appropriate learning progressions (National Academy of Engineering, 2010, 2017). Table 1 provides a summary of proposed “big ideas” for each engineering-literacy dimension founded on previous literature. However, based on the recommendations from the National Academy of Engineering (2017), the authors believe that it is necessary to extend these big ideas for engineering knowledge and practice to establish a taxonomy of engineering concepts and sub-concepts and to make appropriate connections with the engineering habits of mind.

**Problem Statement**

Our world is full of seemingly insurmountable challenges: poverty, food security, and climate change to name a few. Historically, engineering has provided solutions to the world’s most daunting problems. Paramount among these challenges is the need to prepare the next generation of global citizens to solve issues of the ensuing century. While the demands of our world require creative, capable, and diverse problem solving, our children continue to have limited opportunities to engage in authentic engineering as part of a typical educational environment. This may not only be detrimental to our regional, national, and global economic and security success, but also for cultivating informed and participating citizens. Therefore, to solve the most difficult economic, environmental, and societal challenges of the future, one should be driven to advocate for all students to engage in engineering in order to meet these challenges. Such a formidable initiative results in political and economic trials of its own: budget constraints, space in the current school schedule, and teacher professional

![Figure 1. Dimensions of engineering literacy.](image-url)
Development that influence educational practice. Even with these obstacles, the last decade has seen the proliferation of engineering in U.S. elementary, middle, and high schools. However, while engineering education is an emerging trend in P-12 schools, there is a lack of a defined and cohesive educational sequence to potentially serve as the foundation for national P-12 engineering learning progressions and standards. This seems specifically true in regard to the depth of content related to engineering knowledge and practice dimensions of engineering literacy. Therefore, the authors set out to provide educators with the primary components of a viable engineering taxonomic structure for use in P-12 engineering programs to ensure that every child is given the opportunity to think, learn, and act like an engineer. Specifically, this investigation sought to establish agreed-upon concepts and sub-concepts for the development of progressions of learning to articulate and evaluate a sequence of knowledge and practices that students should learn as they progress toward engineering literacy. It is important to note that this study did not include an investigation on the engineering habits of mind, as significant work has already taken place to define and describe these habits.

**Research Objective**

This study sought to answer the question: “If engineering becomes a compulsory subject in school to achieve engineering literacy for all students, what do teachers teach?” In turn, the research was structured to establish a potential epistemological foundation for the study of engineering across P-12 schools, by determining the (1) content organizers, (2) concepts, and (3) sub-concepts for the development of an engineering content taxonomy. This taxonomy can be viewed as necessary for the creation of age-appropriate progressions of learning to be implemented and tested in P-12 classrooms.

![Figure 2. A proposed scaffolding of engineering dimensions of literacy across grade levels.](image)

**Table 1**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Big ideas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering knowledge</td>
<td>• Engineering design is an approach to solving problems or achieving goals</td>
</tr>
<tr>
<td></td>
<td>• Technology is a fundamental attribute of human culture</td>
</tr>
<tr>
<td></td>
<td>• Science and engineering differ in terms of goals, processes, and products</td>
</tr>
<tr>
<td>Engineering practices</td>
<td>• Designing under constraints</td>
</tr>
<tr>
<td></td>
<td>• Using tools and materials</td>
</tr>
<tr>
<td></td>
<td>• Engineering graphics</td>
</tr>
<tr>
<td></td>
<td>• Developing physical models and/or prototypes</td>
</tr>
<tr>
<td></td>
<td>• Research and investigation</td>
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<tr>
<td></td>
<td>• Technical writing</td>
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<tr>
<td></td>
<td>• Mathematical reasoning</td>
</tr>
<tr>
<td></td>
<td>• Project management</td>
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<tr>
<td>Engineering habits of mind</td>
<td>• Systems thinking</td>
</tr>
<tr>
<td></td>
<td>• Creativity</td>
</tr>
<tr>
<td></td>
<td>• Optimism</td>
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<td></td>
<td>• Collaboration</td>
</tr>
<tr>
<td></td>
<td>• Conscientiousness</td>
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<td></td>
<td>• Persistence</td>
</tr>
</tbody>
</table>

Methods

This study employed a modified Delphi method which included a variety of stakeholders involved in the engineering, engineering education, technology and engineering education, and also teacher education communities. The modified Delphi is a semi-structured mixed methods approach involving one qualitative round of investigation followed by two or more quantitative rounds (Helmer & Rescher, 1959). The technique attempts to build a consensus of opinion by asking experts a round of questions, developing more refined questions that are returned to the respondents, and so on. The main reason for the selection of this research methodology was that it provides a feasible approach to develop a consensus among different experts. Hartman and Bell (2017) claim that the Delphi approach is particularly suitable for research projects aiming toward curriculum development for relatively new fields, such as P-12 engineering education, without the existence of prior frameworks. Another advantage considered in this study is that the modified Delphi can be conducted without a face-to-face group meeting through the use of surveys. This advantage allows researchers to involve more experts who would be unable to centrally convene (Delbecq, van de Ven, & Gustafson, 1975). For these advantages, the Delphi methodology has been used in multiple curriculum studies (Bolte, 2008; Hartman, 2016; Kloser, 2014; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003). However, to improve the utility of the Delphi results for the development of progressions of learning, the authors took a more unique approach that involved a series of focus groups as the final round, allowing the relevant stakeholders to debate and refine the results.

In this study, a total of 40 participants—with various professional experiences—were selected and invited across secondary education, post-secondary education, and engineering-related professions (based on the recommendations of national organizations). The participants included teachers and administrators for secondary education; faculty members or administrators in engineering or teacher-education programs; coordinators of P-12 engineering outreach; and technologists, engineers, scientists, or mathematicians working in engineering-related professions. Also, professionals in association administration or leadership, curriculum specialists, state education administrators, and graduate students majoring in engineering and technology education were invited to diversify the expertise for a content structure of P-12 engineering. The details of the selection criteria for each participant group are described in Table 2. Many participants crossed several of the areas of professional experiences. As the modified Delphi process includes multiple rounds usually involving approximately 30 participants (Paré, Cameron, Poba-Nzaou, & Templier, 2013), the authors initially invited 40 individuals who satisfied the selection criteria, anticipating the possibility that some participants may not complete all rounds.

Employing the modified Delphi, this study involved three rounds in survey format and one final Refinement and Development round in a face-to-face focus group setting. In the survey, both core concept and sub-concept were defined and described to the participants. A core concept is a primary idea the participant felt represented the content area. Sub-concepts are content subdivisions that each core concept could be broken into as the next level in structural hierarchy. Throughout the four rounds, the participants were asked to identify, rate, and then verify core concepts and corresponding sub-concepts for both the knowledge and practices dimensions of engineering literacy. The four rounds consisted of:

Round 1: Concept Discovery (identifying important concepts and sub-concepts).
Round 2: Concept Prioritization.
Round 3: Concept Rating.
Final Round: Concept Verifying and Refinement (involving focus groups).

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Selection criteria for participants.</th>
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</thead>
<tbody>
<tr>
<td><strong>Criteria</strong></td>
<td><strong>Secondary education</strong></td>
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<tr>
<td>Education</td>
<td>• Bachelor’s degree in science, engineering/technology, or mathematics education as well as professional development experiences in teaching of engineering</td>
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<tr>
<td>Professional background</td>
<td>• Teaching engineering or technology at secondary level</td>
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<td></td>
<td>• P-12 education administration related to coordination of STEM curriculum</td>
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<td></td>
<td>• Teaching or research in teacher education</td>
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<td></td>
<td>• Engineering outreach coordination</td>
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</table>
The survey questions for the initial three Delphi rounds were answered anonymously through an online survey tool. For these initial rounds, an average of 26 participants completed each questionnaire. For the final round, eight focus groups involving 32 participants were organized in consideration of their professional experiences. Table 3 presents the overall participant backgrounds for each round of the study.

Table 3
Participant backgrounds overall and for rounds 1, 2, 3, and 4.

<table>
<thead>
<tr>
<th>Professional experience</th>
<th>Invited</th>
<th>Round 1</th>
<th>Round 2</th>
<th>Round 3</th>
<th>Final round</th>
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<tr>
<td>Secondary education</td>
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<tr>
<td>• Engineering/technology teacher</td>
<td>26</td>
<td>9</td>
<td>13</td>
<td>15</td>
<td>21</td>
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<tr>
<td>• Science teacher</td>
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<td>• Mathematics teacher</td>
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<td>• K-12 administrator</td>
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<td>• Other</td>
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<td>Post-secondary education</td>
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<tr>
<td>• Engineering faculty</td>
<td>23</td>
<td>18</td>
<td>14</td>
<td>12</td>
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<tr>
<td>• Teacher education faculty</td>
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<td>• Science faculty</td>
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<td>• Engineering administrator</td>
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<td>• Teacher education administrator</td>
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<td>• Outreach coordinator</td>
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<td>• Other</td>
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<tr>
<td>Professional</td>
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<td>• Engineering technologist/technician</td>
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<td>5</td>
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<td>4</td>
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<td>• Civil engineer</td>
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<td>• Mechanical engineer</td>
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<td>• Electrical/computer engineer</td>
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<td>• Biomedical engineer</td>
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<td>• Industrial engineer</td>
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<td>• Scientist</td>
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<td>• Mathematician</td>
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<td>• Other</td>
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<tr>
<td>Other</td>
<td>15</td>
<td>2</td>
<td>6</td>
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<td>13</td>
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<tr>
<td>• Professional association administration/leadership</td>
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<tr>
<td>• Outreach/curriculum specialist</td>
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<tr>
<td>• Other (state education administrator, graduate student)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total participants</td>
<td>40</td>
<td>22</td>
<td>24</td>
<td>26</td>
<td>32</td>
</tr>
</tbody>
</table>

Note. Many participants crossed several of professional experience categories.

The survey questions for the initial three Delphi rounds were answered anonymously through an online survey tool. For these initial rounds, an average of 26 participants completed each questionnaire. For the final round, eight focus groups involving 32 participants were organized in consideration of their professional experiences. Table 3 presents the overall participant backgrounds for each round of the study.

For Round 1, the concept discovery questionnaire in Appendix A was sent to the participants, who were given one week to submit their responses. The questionnaire was developed based on the Delphi approach enacted by Wells (1992) to establish a taxonomy for the study of biotechnology in secondary school. The questionnaire provided a brief overview of the study as well as several links to open resources for review such as the National Academies Taxonomy of Fields and Sub-Fields, the Fundamentals of Engineering Exam Resources, and the National Academy of Engineering’s Standards for K-12 Engineering Education Report. Also, the questionnaire presented a potential taxonomic structure for the knowledge and practice dimensions of engineering literacy which is provided in Figure 3. As seen in Figure 3, the knowledge dimension included the four content areas of mechanical, electrical, civil, and chemical, and the practice dimension included the four content areas of engineering design, material processing, quantitative analysis, and ethics and society (later renamed professional conventions). The structure was founded on the synthesis of relevant literature (Carr et al., 2012; Custer & Erekson, 2008; Merrill et al., 2009; National Academy of Engineering, 2009, 2010; Sneider & Rosen, 2009) as well as the National Academies’ Taxonomy of Engineering (NASEM, 2006), the Fundamentals of Engineering Exams (National Council of Examiners for Engineering & Surveying, 2017), first-year engineering programs (Strimel, Krause, Hensel, Kim, & Grubbs, 2018) and the Accreditation Board for Engineering and Technology disciplines of engineering, engineering technology, and computing (Engineering Accreditation Commission, 2016). The Delphi participants reviewed the taxonomic structure and identified and prioritized the core concepts and sub-concepts for each content area to serve as a foundation for the knowledge and practice dimensions of engineering literacy.
Accordingly, for Round 1, the participants were asked to identify core concepts and corresponding sub-concepts for each of the eight content areas through the following questions:

- What are the main core concepts you feel represent the conceptual knowledge of each content area appropriate for the secondary study of engineering?
- Under each of the designated concepts for each content area, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy?

Also, the participants could provide feedback on, or suggest modifications for, the content areas that were identified for the potential taxonomic structure. A total of 22 participants responded to the Round 1 survey. The authors combined the participants’ qualitative answers to create the list of concepts and corresponding sub-concepts for each content area for Round 2.

For Round 2, the concept prioritization questionnaire was sent to the participants and they were given one week to submit their responses. Based on the Round 1 results, the Round 2 concept prioritization questionnaire asked the participants to review and then rate each of the concepts and sub-concepts for every content area on a six-point Likert scale (1 = not important to 6 = critical). Also, the participants could add a justification or clarification for any item, as needed, in the comment sections. A total of 24 participants completed the Round 2 questionnaire. The authors calculated the mean and standard deviation of each concept/sub-concept and collected the qualitative responses for the next round. The items rated below 3.00 were to be eliminated for Round 3.

For Round 3, the concept-rating questionnaire was sent to the participants and they were, again, given one week to provide their response. The Round 3 concept-rating questionnaire was developed based on the participants’ quantitative and qualitative responses to Round 2. Thus, the questionnaire included revised lists of concepts and sub-concepts for each content area and the mean and standard deviation of each concept. Then, the participants were asked to rate each concept again for its importance and to add comments, if needed, in the same way as Round 2. A total of 26 participants responded to the Round 3 questionnaire. The mean and standard deviation were calculated for each concept and collected qualitative responses for the final round. The items rated below 3.00 were to be eliminated for the final round.

Lastly, the final round involved eight focus groups. These focus groups were essential to this project and differentiate this study from others conducted previously. Oftentimes, Delphi studies are done within a vacuum without direct debate between both content experts and practicing educators. This may be one reason why previous efforts have not been widely employed in the classroom. Additionally, the focus groups enabled the research team to solicit participation of much needed broader expertise in areas of elementary education and curriculum development. The focus groups brought together 32 experts from the education, engineering education, technology education, and engineering communities. Experts were invited based on participation from the preceding Delphi study (20) and recommendations from various stakeholders (e.g., ITEEA, ASEE, and National Academy of Engineering) with an interest in the research (12). The participants were
After the three Delphi rounds were completed and an initial taxonomy emerged, eight focus groups were organized to deliberate the results in the final round. While reviewing and answering the provided guiding questions, the participants recommended the following overarching revisions to improve the utility of the taxonomy: (a) general improvements in regards to the wording or structures of concepts, (b) removing the “career-focused” content areas within the Engineering Knowledge dimension (mechanical, electrical, civil, and chemical), and (c) integrating the duplicated/overlapping concepts across the content areas to form crosscutting concepts. These revisions were recommended to (a) improve the taxonomy terminology, (b) avoid the potential confusion and concerns related to these content areas being
viewed as specific engineering careers rather than just a means to organize content, and (c) reduce the overwhelming number of concepts and sub-concepts. Accordingly, the biggest recommended change involved the removal of the content areas for the Engineering Knowledge dimension. However, it is important to note that these content area labels were viewed as a necessary structure to initially determine what concepts were important across each area. However, once the concepts important to each content area were determined through the initial rounds, the content area titles could be removed and the crosscutting concepts could be identified—allowing the removal of duplicated concepts. Figure 4 illustrates an example of how the emerging taxonomy was revised, wherein the crosscutting concepts relating to the field of statics (i.e., force systems, equilibrium, inertia) were converged from the mechanical and civil content areas to form a single core concept. Removing the content area classifications and creating a combined core concept, in this case the field of statics, can allow for more flexibility in development of progressions of learning. The complete revised taxonomy is provided in Tables 7 and 8.

**Discussions**

**Utility of the Taxonomy**

While millions of students participate in formal P-12 engineering coursework (Marshall & Berland, 2012), a major problem has been the lack of broadly accepted P-12 engineering standards and a shared understanding of the role of engineering within primary and secondary schools (Chandler, Fontenot, & Tate, 2011). As an operationalized and sequenced progression of engineering learning continues to be lacking at the P-12 level, the authors hope that the taxonomy resulting from this study can serve as the kernel for expanding the definition of engineering literacy. Moreover, such consistency is expected to ensure a more equitable approach to the delivery of engineering at the P-12 level, as teacher preparation programs, professional development opportunities, and alternative licensures programs can be built around this framework for the most comprehensive support model possible. As such, this work can ultimately help set the foundation for the development of learning progressions and standards to establish coherent educational pathways in engineering. However, one may question how this work differs from some previous studies. Therefore, it is important to further discuss the context of this study, which provides several reasons why this work can be considered unique and why the results can have utility value for P-12 classrooms.

First, the methods were established to specifically address the recommendations set forth by the National Academy of Engineering (2010), which included bringing content experts and grade-level experts together. To do so, this work enacted a strategy that enabled participants to identify engineering concepts individually while also affording an opportunity to refine the concepts through debate and deliberation in focus group settings. As stated by the National Academy of Engineering (2017), “the historical lack of involvement by K-12 teachers in education policy and decision making is particularly

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**Table 4**

Summary of Delphi study results.

<table>
<thead>
<tr>
<th>Content area</th>
<th>Round 1</th>
<th>Round 2</th>
<th>Round 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of concepts</td>
<td>Number of concepts</td>
<td>Average of ratings</td>
</tr>
<tr>
<td>Mechanical</td>
<td>7</td>
<td>67</td>
<td>4.61</td>
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<tr>
<td>Sub-concepts</td>
<td>43</td>
<td>43</td>
<td>4.14</td>
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<tr>
<td>Electrical</td>
<td>8</td>
<td>8</td>
<td>4.64</td>
</tr>
<tr>
<td>Sub-concepts</td>
<td>63</td>
<td>63</td>
<td>4.22</td>
</tr>
<tr>
<td>Civil</td>
<td>8</td>
<td>8</td>
<td>4.37</td>
</tr>
<tr>
<td>Sub-concepts</td>
<td>50</td>
<td>51</td>
<td>4.05</td>
</tr>
<tr>
<td>Chemical</td>
<td>10</td>
<td>10</td>
<td>4.32</td>
</tr>
<tr>
<td>Sub-concepts</td>
<td>53</td>
<td>53</td>
<td>3.98</td>
</tr>
<tr>
<td>Engineering design</td>
<td>9</td>
<td>9</td>
<td>5.47</td>
</tr>
<tr>
<td>Sub-concepts</td>
<td>51</td>
<td>52</td>
<td>5.10</td>
</tr>
<tr>
<td>Material processing</td>
<td>8</td>
<td>8</td>
<td>4.49</td>
</tr>
<tr>
<td>Sub-concepts</td>
<td>34</td>
<td>35</td>
<td>4.16</td>
</tr>
<tr>
<td>Quantitative analysis</td>
<td>6</td>
<td>6</td>
<td>5.29</td>
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<tr>
<td>Sub-concepts</td>
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<td>34</td>
<td>4.77</td>
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<tr>
<td>Professional conventions</td>
<td>6</td>
<td>6</td>
<td>4.81</td>
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<tr>
<td>Sub-concepts</td>
<td>38</td>
<td>39</td>
<td>4.46</td>
</tr>
</tbody>
</table>

*Note. The rating scale: 1–6 (1 = not important; 6 = critical).*
<table>
<thead>
<tr>
<th>Mechanical Sciences for Mechanical Engineering</th>
<th>Electrical Sciences for Electrical Engineering</th>
<th>Civil Engineering Sciences for Civil Engineering</th>
<th>Chemical Engineering Sciences for Chemical Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Systems</td>
<td>Properties of Materials (chemical, mechanical, and thermal)</td>
<td>Force</td>
<td>Applications of Inorganic Chemistry</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>Current, Voltage, Charge, Energy, and Amp=Power</td>
<td>Equilibrium</td>
<td>Applications of Organic Chemistry (e.g., biofuels)</td>
</tr>
<tr>
<td>Inertia</td>
<td>Forces (e.g., charges, conductors)</td>
<td>Inertia</td>
<td>Chemical, Electrical, Mechanical and Physical Properties (including potential hazards)</td>
</tr>
<tr>
<td>Friction</td>
<td>Voltage and Work</td>
<td>Friction</td>
<td>Material Types and Compatibilities</td>
</tr>
<tr>
<td>Centroids and Moments</td>
<td>Electrical Power</td>
<td>Centroids and Moments</td>
<td>Corrosion</td>
</tr>
<tr>
<td>Rigid bodies</td>
<td>Force</td>
<td>Rigid Bodies</td>
<td>Nanoscience</td>
</tr>
<tr>
<td>Newton’s Second Law</td>
<td>Motors and Generators</td>
<td>Resultant Calculations</td>
<td>Chemical Reaction and Catalysis</td>
</tr>
<tr>
<td>Work and Energy</td>
<td>Electrical Materials</td>
<td>Shear and Moment Diagrams</td>
<td>Reaction rate, Rate Constant, and Order</td>
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<tr>
<td>Impulse-Momentum</td>
<td>Electro-magnetics</td>
<td>Hydrologic Systems</td>
<td>Conversion, Yield, and Selectivity</td>
</tr>
<tr>
<td>Mechanics of Materials</td>
<td>Voltage Regulation</td>
<td>Hydrology and Hydraulics</td>
<td>Chemical Equilibrium</td>
</tr>
<tr>
<td>Stress Types (axial, bending, torsion, shear)</td>
<td>Transmission and Distribution</td>
<td>Water Distribution and Collection Systems</td>
<td>Fluid Mechanics and Dynamics</td>
</tr>
<tr>
<td>Stress-Strain Analysis</td>
<td>Series and Parallel Equivalent Circuits</td>
<td>Structural Analysis</td>
<td>Bernoulli’s Principle</td>
</tr>
<tr>
<td>Static Equilibrium</td>
<td>Ohm’s Laws and Kirchhoff’s Laws</td>
<td>Physical Properties of Building Materials</td>
<td>Flow</td>
</tr>
<tr>
<td>Material Deformations</td>
<td>Power and Energy</td>
<td>Deflection</td>
<td>Pumps, Turbines, and Compressors</td>
</tr>
<tr>
<td>Material Equations</td>
<td>Resistance, Capacitance, and Inductance</td>
<td>Deformations</td>
<td>Fluid Properties</td>
</tr>
<tr>
<td>Phase Diagrams</td>
<td>Wave Forms</td>
<td>Column and Beam Analysis</td>
<td>Heat Transfer</td>
</tr>
<tr>
<td>Heat Treating</td>
<td>Analog vs. Digital Signals</td>
<td>Mohr’s Circle (2D graphical representation of the transformation law for the Cauchy stress tensor)</td>
<td>Conductive, Convective, and Radiative Heat</td>
</tr>
<tr>
<td>Dynamics and Vibrations</td>
<td>Electronics</td>
<td>Implementation of Design Codes</td>
<td>Heat Transfer Coefficients</td>
</tr>
<tr>
<td>Scalars</td>
<td>Instrumentation and Components (physical components and measurement devices)</td>
<td>Infrastructure</td>
<td>Energy</td>
</tr>
<tr>
<td>Vectors</td>
<td>Semiconductor</td>
<td>Street, Highway, and Intersection Design</td>
<td>Work, Energy, and Power</td>
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<tr>
<td>Resistance</td>
<td>Control Systems</td>
<td>Transportation Planning and Control (safety, capacity, flow)</td>
<td>Energy Balance</td>
</tr>
<tr>
<td>Mechanical Design</td>
<td>Sensors</td>
<td>Traffic Design</td>
<td>Fuels</td>
</tr>
<tr>
<td>Manufacturing Processes</td>
<td>Closed and Open Loop and Feedback (systems, system response)</td>
<td>Pavement Design</td>
<td>Energy Transfer</td>
</tr>
<tr>
<td>Machine Control</td>
<td>Block Diagramming</td>
<td>Surveying</td>
<td>Thermodynamic Properties, Laws, and Processes</td>
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<tr>
<td>Electro-mechanical Systems</td>
<td>Digital Systems</td>
<td>Topographical Surveys</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>Basic Electricity</td>
<td>Programmable Logic Devices</td>
<td>Route Survey</td>
<td>Gas Properties</td>
</tr>
<tr>
<td>Circuits</td>
<td>Logic Simplification (Boolean logic, K-mapping)</td>
<td>Leveling</td>
<td>Power Cycles and Efficiency</td>
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<tr>
<td>Motors and Generators</td>
<td>Number Systems</td>
<td>Coordinate System</td>
<td>Mass Transfer and Separation</td>
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<tr>
<td>Electric Charge</td>
<td>Logic State and Gate Arrays</td>
<td>Project Management in Civil Engineering</td>
<td>Molecular Diffusions</td>
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<tr>
<td>Magnetism</td>
<td>State Machine Design</td>
<td>Project Planning and Management Economics</td>
<td>Separation Systems</td>
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<tr>
<td>Fluid Mechanics</td>
<td>(microcontrollers/programming)</td>
<td>Safety</td>
<td>Equilibrium State Methods</td>
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<td>Fluid Properties</td>
<td>Communication Technology</td>
<td>Project Delivery</td>
<td>Humidification and Drying</td>
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<td>Fluid Statics and Motion</td>
<td>Digital Communications</td>
<td>Human Resource Management</td>
<td>Continuous Contact Methods</td>
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<td>(Bernoulli’s equation)</td>
<td>Telecommunications</td>
<td>Verifying Local Codes</td>
<td>Convective Mass Transfer</td>
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<td>Hydraulics</td>
<td>Fiber Optics (photons)</td>
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<td>Process Controls and Systems</td>
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<td>Erosion Control</td>
<td>Process Flow, Piping, and Injection Diagrams</td>
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<td>Geological Properties and Classification</td>
<td>Recycle and Bypass Processes</td>
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<td>Industrial Chemical Operations</td>
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<td>Processors and Microprocessors</td>
<td>Bearing Capacity</td>
<td>Biological/Chemical Applications</td>
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<td>Drainage Systems</td>
<td>Bio-molecular Engineering</td>
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<td>Algorithms</td>
<td>Erosion Control</td>
<td>Biotechnology</td>
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<td>Biochemical Engineering</td>
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<td>Memory</td>
<td>Ground and Surface Water Quality</td>
<td>Pharmaceuticals</td>
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<td>HVAC Processes</td>
<td>Programming Languages</td>
<td>Wastewater Management (disposal)</td>
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<td>Psychometrics</td>
<td>Emerging Fields in Electrical Engineering</td>
<td>Environmental Impact Regulations and Tests</td>
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<td>Emerging Mechanical Engineering</td>
<td>Biomedical Engineering Applications (instrumentation, imaging, biometrics)</td>
<td>Natural Systems</td>
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<td>Virtual System</td>
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<td>Nanotechnology</td>
<td>Cybersecurity</td>
<td></td>
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</tr>
<tr>
<td>Ocean Engineering</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5
Emerging content taxonomy for engineering knowledge.
a problem for education in engineering” (p. vii). Second, the project was framed in a manner to move beyond identifying only “broad” engineering concepts (e.g., teamwork, problem-solving, design, creativity, and communication) to classifying and recognizing the in-depth fundamental engineering knowledge that informs engineering practice, as well as the technical concepts to perform such practices with increased sophistication (e.g., problem framing, decision-making techniques, fabrication processes, computational thinking and tools, mechanics of materials,
thermodynamics, mass transfer and separation, and hydrologic systems). This also aligns, and supplements, the content components of the Standards for preparation and professional development for teachers of engineering (Farmer, Klein-Gardner, & Nadelson, 2014). Third, the study was framed in a use-inspired context, wherein the results of the process were to be implemented and tested in schools through a research–practitioner partnership leveraging the curriculum space provided by the Technology and Engineering Education school subject in a state in which it was required for graduation. Through this approach, the authors hope to enhance the utility value of the study’s results and support achieving engineering literacy for all students.

Defining Engineering Literacy

As mentioned, the taxonomy established through this research and development work can help to further define engineering literacy and, as such, provide a cohesive lens in which to bind the concepts, practices, and habits of mind that can be intentionally taught for learners to become engineering literate. When considering how the results from this study may help define engineering literacy for all students, it is necessary to discuss the term “core concepts.” While the concepts identified in this study were originally conceived as “core” to engineering learning, it is reasonable to suggest that not all the scientific, mathematical, and technical concepts identified are essential for fundamental engineering literacy. The Engineering Knowledge dimension could be further defined as the scientific, mathematical, and technical concepts that students should appreciate and be able to draw upon, when appropriate, to better perform the practices of engineering. One would not expect a student to fully understand each of the Engineering Knowledge concepts in depth by the end of secondary school. However, to be engineering-literate individuals, they must be able to deploy their Engineering Habits of Mind as the thinking strategies to acquire and apply the appropriate Engineering Knowledge, along with their competence in Engineering Practice, to confront and solve the problems in which they encounter. For example, Table 9 outlines a proposed draft for a blueprint toward engineering literacy that leverages the results of this study to extend the depth in which the dimensions of literacy are defined. As a result, this blueprint can help provide a lens, not for compliance but for coherence, in conducting research to investigate and improve the impact of engineering education in P-12 settings. This can be important as the impact of engineering within P-12 schools needs to be well documented in the literature to continue garnering support from the general public and through legislation. As Chandler et al. (2011) indicate, there has been limited research that demonstrates how P-12 engineering curricula can help all students to develop the “habits of mind” or the engineering skill sets that can contribute to a technically proficient and informed citizenry for the 21st century.

Addressing Coherence to Achieve Engineering Literacy for All

The National Assessment of Educational Progress (2016) indicates that only a small portion of the nation’s youth are intentionally taught the concepts of engineering and design throughout their educational experiences. Change the Equation (2016) also states that less than half of the nation’s eighth graders were on track to become proficient in using engineering concepts and practices to conceive optimal solutions for authentic problems. Therefore, a major objective of developing a content taxonomy of engineering is to help educators develop and implement curriculum and instruction that allows for coherent educational pathways across the country based on a consistent, operational definition of engineering literacy. As an
<table>
<thead>
<tr>
<th>Concepts</th>
<th>Sub-concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statics</td>
<td>• Resultants of force systems</td>
</tr>
<tr>
<td></td>
<td>• Equivalent force systems</td>
</tr>
<tr>
<td></td>
<td>• Equilibrium of rigid bodies</td>
</tr>
<tr>
<td>Dynamics</td>
<td>• Kinematics (e.g., particles and rigid bodies)</td>
</tr>
<tr>
<td></td>
<td>• Mass moments of inertia</td>
</tr>
<tr>
<td></td>
<td>• Force acceleration (e.g., particles and rigid bodies)</td>
</tr>
<tr>
<td>Mechanics of materials</td>
<td>• Stress types and transformations</td>
</tr>
<tr>
<td></td>
<td>• Material characteristics, properties, and composition (e.g., heat treating)</td>
</tr>
<tr>
<td></td>
<td>• Stress-strain analysis</td>
</tr>
<tr>
<td></td>
<td>• Material deformations</td>
</tr>
<tr>
<td>Fluid mechanics</td>
<td>• Fluid properties</td>
</tr>
<tr>
<td></td>
<td>• Pumps, turbines, and compressors</td>
</tr>
<tr>
<td></td>
<td>• Lift, drag, and fluid resistance</td>
</tr>
<tr>
<td>Mechanical design</td>
<td>• Machine elements (e.g., springs, pressure vessels, beams, piping, cams, and gears)</td>
</tr>
<tr>
<td>Circuit theory</td>
<td>• Series and parallel circuits</td>
</tr>
<tr>
<td></td>
<td>• Ohm’s laws</td>
</tr>
<tr>
<td></td>
<td>• Kirchhoff’s laws</td>
</tr>
<tr>
<td></td>
<td>• Resistance, capacitance, and inductance</td>
</tr>
<tr>
<td>Electrical power</td>
<td>• Motors and generators</td>
</tr>
<tr>
<td></td>
<td>• AC and DC</td>
</tr>
<tr>
<td></td>
<td>• Electrical materials</td>
</tr>
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<td></td>
<td>• Electro-magnetics</td>
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<td>• Instrumentation</td>
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<td>• Components</td>
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<td>• Integrated circuits</td>
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<td>Communication</td>
<td>• Digital communications</td>
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<td>• Computer software</td>
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<td>• Processors and microprocessors</td>
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<tr>
<td>Thermodynamics</td>
<td>• Thermodynamic properties, laws, and processes</td>
</tr>
<tr>
<td></td>
<td>• Equilibrium</td>
</tr>
<tr>
<td>Mass transfer and separation</td>
<td>• Molecular diffusions</td>
</tr>
<tr>
<td></td>
<td>• Separation systems</td>
</tr>
<tr>
<td>Chemical applications</td>
<td>• Equilibrium state methods</td>
</tr>
<tr>
<td></td>
<td>• Applications of inorganic chemistry</td>
</tr>
<tr>
<td></td>
<td>• Applications of organic chemistry</td>
</tr>
<tr>
<td></td>
<td>• Chemical, electrical, mechanical, and physical properties (including potential hazards)</td>
</tr>
<tr>
<td>Chemical reactions and catalysts</td>
<td>• Reaction rate, rate constant, and order</td>
</tr>
<tr>
<td>Process design</td>
<td>• Process controls and systems</td>
</tr>
<tr>
<td></td>
<td>• Process flow, piping, and instrumentation diagrams</td>
</tr>
<tr>
<td>Structural analysis</td>
<td>• Physical properties of building materials</td>
</tr>
<tr>
<td></td>
<td>• Deflection</td>
</tr>
<tr>
<td>Hydrologic systems</td>
<td>• Hydrology</td>
</tr>
<tr>
<td></td>
<td>• Water distribution and collection systems</td>
</tr>
<tr>
<td></td>
<td>• Watershed analysis</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>• Street, highway, and intersection design</td>
</tr>
<tr>
<td></td>
<td>• Transportation planning and control (safety, capacity, flow)</td>
</tr>
<tr>
<td>Geotechnics</td>
<td>• Laboratory and field tests</td>
</tr>
<tr>
<td></td>
<td>• Erosion control</td>
</tr>
<tr>
<td></td>
<td>• Geological properties and classifications</td>
</tr>
<tr>
<td></td>
<td>• Soil characteristics</td>
</tr>
<tr>
<td>Environmental</td>
<td>• Ground and surface water quality</td>
</tr>
<tr>
<td>considerations</td>
<td>• Wastewater management</td>
</tr>
</tbody>
</table>

|                      | • Frames and trusses                                                       |
|                      | • Centroid of area                                                         |
|                      | • Area moments of inertia                                                 |
|                      | • Impulse momentum (e.g., particles and rigid bodies)                      |
|                      | • Work, energy, and power (e.g., particles and rigid bodies)               |
|                      | • Material equations                                                       |
|                      | • Phase diagrams                                                           |
|                      | • Mohr’s circle                                                            |
|                      | • Young’s modulus                                                          |
|                      | • Fluid statics and motion (Bernoulli’s equation)                          |
|                      | • Pneumatics and hydraulics                                                |
|                      | • Manufacturing processes                                                  |
|                      | • Machine control                                                          |
|                      | • Wave forms                                                               |
|                      | • Signals                                                                  |
|                      | • Current, voltage, charge, energy, power, and work                        |
|                      | • Closed and open loop and feedback (systems, system response)             |
|                      | • Digital electronics (e.g., gates and logic)                               |
|                      | • Gas properties                                                           |
|                      | • Power cycles and efficiency                                              |
|                      | • Humidification and drying                                                |
|                      | • Continuous contact methods                                               |
|                      | • Convective mass transfer                                                 |
|                      | • Material types and compatibilities                                       |
|                      | • Corrosion                                                                |
|                      | • Membrane science                                                         |
|                      | • Chemical equilibrium                                                     |
|                      | • Fuels                                                                    |
|                      | • Recycle and bypass processes                                             |
|                      | • Industrial chemical operations                                           |
|                      | • Deformations                                                             |
|                      | • Column and beam analysis                                                 |
|                      | • Implementation of design codes                                           |
|                      | • Open channel                                                             |
|                      | • Closed conduits (pressurized)                                            |
|                      | • Pumping stations                                                         |
|                      | • Laboratory and field tests                                               |
|                      | • Traffic design                                                           |
|                      | • Pavement design                                                          |
|                      | • Bearing capacity                                                         |
|                      | • Drainage systems                                                         |
|                      | • Foundations and retaining walls                                          |
|                      | • Slope stability                                                          |
|                      | • Environmental impact regulations and tests                               |

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Table 8  
Revised content taxonomy for engineering practice.

<table>
<thead>
<tr>
<th>Core concepts</th>
<th>Sub-concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering Design</td>
<td>Problem framing</td>
</tr>
<tr>
<td>Research and investigation</td>
<td>Information gathering</td>
</tr>
<tr>
<td>Ideation</td>
<td>Data collection and organization methods</td>
</tr>
<tr>
<td>Prototyping</td>
<td>Spatial visualization (e.g., sketching)</td>
</tr>
<tr>
<td>Decision making</td>
<td>Testing and modification (digital and physical)</td>
</tr>
<tr>
<td>Decision making</td>
<td>Material selection</td>
</tr>
<tr>
<td>Project management</td>
<td>Evidence/data-driven decisions</td>
</tr>
<tr>
<td>Design methods</td>
<td>Application of STEM principles</td>
</tr>
<tr>
<td>Design methods</td>
<td>Balancing trade-offs</td>
</tr>
<tr>
<td>Engineering communication</td>
<td>Initiating and planning</td>
</tr>
<tr>
<td>Engineering communication</td>
<td>Scope, time, and cost management</td>
</tr>
<tr>
<td>Materials Processing</td>
<td>Engineering graphics</td>
</tr>
<tr>
<td>Measurement and precision</td>
<td>Dimensioning and tolerances</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>2D computer-aided design</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Tool selection</td>
</tr>
<tr>
<td>Material classification</td>
<td>Product assembly</td>
</tr>
<tr>
<td>Joining</td>
<td>Hand tools</td>
</tr>
<tr>
<td>Forming</td>
<td>Composites</td>
</tr>
<tr>
<td>Machining</td>
<td>Metals and alloys</td>
</tr>
<tr>
<td>Finishing</td>
<td>Adhesion</td>
</tr>
<tr>
<td>General safety</td>
<td>Forging</td>
</tr>
<tr>
<td>Computational thinking</td>
<td>Extruding</td>
</tr>
<tr>
<td>Computational tools</td>
<td>Drilling</td>
</tr>
<tr>
<td>Data Collection, Analysis, and Communication</td>
<td>Cutting</td>
</tr>
<tr>
<td>System analytics</td>
<td>Milling</td>
</tr>
<tr>
<td>Modeling and Simulation</td>
<td>Design for manufacture</td>
</tr>
<tr>
<td>Engineering algebra</td>
<td>Additive manufacturing</td>
</tr>
<tr>
<td>Engineering geometry</td>
<td>Tool selection</td>
</tr>
<tr>
<td>Engineering statistics and probability</td>
<td>Product assembly</td>
</tr>
<tr>
<td>Engineering calculi</td>
<td>Hand tools</td>
</tr>
<tr>
<td>Engineering calculi</td>
<td>Machine safety</td>
</tr>
<tr>
<td>Engineering calculi</td>
<td>Metals and alloys</td>
</tr>
<tr>
<td>Engineering calculi</td>
<td>Adhesion</td>
</tr>
<tr>
<td>Engineering calculi</td>
<td>Forging</td>
</tr>
<tr>
<td>Engineering calculi</td>
<td>Extruding</td>
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<td>Drilling</td>
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<td>Engineering calculi</td>
<td>Product assembly</td>
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<td>Hand tools</td>
</tr>
<tr>
<td>Engineering calculi</td>
<td>Machine safety</td>
</tr>
<tr>
<td>Engineering calculi</td>
<td>Metals and alloys</td>
</tr>
</tbody>
</table>
effort to resolve the paucity of clarity, this study highlights the importance of a consistent epistemic basis for engineering and proposes a foundation for a coherent framework for P-12 engineering learning.

These results can be valuable in promoting diversity in engineering by modeling equity and inclusion through the development and implementation of comprehensive learning progressions of engineering concepts from kindergarten to grade 12 and beyond. This attention to coherence between grade bands can ensure that any curricular framework or standards reflect all the key stages in a learning progression that will not require additional, out-of-school opportunities to fill knowledge gaps—which put students without these experiences at a disadvantage (K-12 Computer Science Framework, 2016). Also, the way in which these results are used for the development of a curricular framework should intentionally model learning experiences that are contextualized in ways that are socially relevant and culturally responsive to students. This can play a major role in addressing the misperceptions around careers in engineering and can help guide the creation of educational experiences that reach all students.

A Foundation for Progressions of Learning in Engineering

As researchers and practitioners leverage the taxonomy in this paper to advance quality P-12 engineering education (Figure 5), effective engineering curricula and instruction will require an understanding of how students engage with and learn engineering habits of mind, practices, and concepts and sub-concepts. As discussed earlier, research on student learning of engineering is limited. Understanding how students progress through learning is paramount to guide P-12 engineering education when considering framework, curriculum, and instruction development and refinement. A major objective of this research was to establish an engineering content taxonomy to support the creation of developmentally appropriate student progressions of learning for P-12 schools. These progressions of learning can provide a defined and cohesive educational sequence to help guide engineering curriculum and instruction. As detailed in Figure 2, this could aid in scaffolding instruction to build from explicitly developing engineering habits at a young age to teaching in-depth concepts to inform engineering practice in high school.

Progressions of learning are defined as a sequenced set of subskills or bodies of enabling knowledge that students must master to achieve a curriculum target (Popham, 2008). Marzano (2010) posits that, “national and state standards often do not provide guidance in regards to the building blocks necessary to reach the designated learning goals” (p. 3). Therefore, progressions of learning will be necessary for the planning and assessment of engineering literacy at the P-12 level. Aligning to the work of Fonger and colleagues (2018), progressions of learning in engineering can serve as a “form of curriculum research that advances a linked understanding of students learning over time through careful articulation of a curricular framework and progression, instructional sequence, assessments, and levels of sophistication in student learning” (p. 30). Consequently, sample progressions of learning in engineering can be developed by leveraging the taxonomy created through this study. It is important to note that the authors have purposefully used the term progression of learning instead of learning progression, as they understand that this work can only be used to support “a progression of learning” and not “the learning progression.” As discussed by Duncan and Hmelo-Silver (2009), a learning progression in science education includes a combined focus of content and practice, is bound by an
### Engineering Habits of Mind

| Optimism | Engineers, as a general rule, believe that things can always be improved. Just because it hasn’t been done yet, doesn’t mean it can’t be done. Good ideas can come from anywhere and engineering is based on the premise that everyone is capable of designing something new or different. |
| Persistence | Failure is expected, even embraced, as engineers work to optimize the solution to a particular challenge. Engineering—particularly engineering design—is an iterative process. It is not about trial and error. It is trying and learning and trying again. |
| Collaboration | Engineering successes are built through collaboration and communication. Teamwork is essential. |
| Creativity | Being able to look at the world and identify new patterns or relationships or imagine new ways of doing things is something at which engineers excel. Finding new ways to apply knowledge and experience is essential in engineering design and is a key ingredient of innovation. |
| Conscientiousness | Engineering has a significant ethical dimension. The technologies and methods that engineers develop can have a profound effect on people’s lives. That kind of power demands a high level of responsibility to consider others and to consider the moral issues that may arise from the work. |
| System thinking | Our world is a system made up of many other systems. Things are connected in remarkably complex ways. To solve problems, or to truly improve conditions, engineers need to be able to recognize and consider how all those different systems are connected. |

### Engineering Practice

| Engineering design | • Problem framing |
| • Information gathering |
| • Ideation |
| • Prototyping |
| • Engineering graphics |
| • Measurement and precision |
| • Manufacturing |
| • Fabrication |
| • Material classification |
| • Joining |
| • Computational thinking |
| • Computational tools |
| • Data collection, analysis, and communication |
| • Project management |
| • Design methods |
| • Design communication |
| • Casting/molding/forming |
| • Separating/machining |
| • Conditioning/finishing |
| • Safety |
| • System analytics |
| • Modeling and simulation |

### Engineering Knowledge

| Engineering sciences | • Statics |
| • Mechanics of materials |
| • Dynamics |
| • Thermodynamics |
| • Fluid mechanics |
| • Professional ethics |
| • Workplace ethics |
| • Honoring intellectual property |
| • Impacts of technology |
| • Role of society in technological development |
| • Engineering-related careers |
| • Mass transfer and separation |
| • Chemical reactions and catalysis |
| • Circuit theory |
| • Heat transfer |

### Engineering mathematics

| Engineering algebra |
| • Engineering geometry and trigonometry |
| • Electrical power |
| • Communication technologies |
| • Computer architecture |
| • Process design |
| • Structural analysis |
| • Environmental considerations |
| • Engineering statistics and probability |
| • Engineering calculus |
| • Hydrologic systems |
| • Transportation infrastructure |
| • Geotechnics |
| • Chemical applications |
| • Mechanical design |
| • Electronics |

### Engineering technical applications

| Decision making |
| • System analytics |
| • Modeling and simulation |

---

Table 9

Proposed expanded draft of the dimensions of engineering literacy.

Note. The dimensions of literacy are based on the following works: International Technology Education Association (1996); National Academy of Engineering & National Research Council (2002, 2006); and A framework for K-12 science education: Practices, crosscutting concepts, and core ideas (2012). The big ideas are synthesized from the following works: Carr et al. (2009, p. 101); Merrill et al. (2009); National Academy of Engineering (2009, pp. 151–152; 2010, pp. 35–36); Sneider & Rosen (2009, p. 131). The engineering habits of mind definitions are provided by the National Academy of Engineering (2018) LinkEngineering Educator’s Exchange. The concepts for the Engineering Knowledge and Engineering Practice dimensions emerged from this study. In addition, the results of this study included sub-concepts for each concept, which are not provided in this table, to support the scaffolding of engineering instruction.

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To provide an example of how the taxonomy can be leveraged to form progressions of learning, the authors created a Progression of Learning in Engineering (PLiE) template. Learning progressions are typically presented as “visual and conceptual maps that explain how students might move from simpler to more sophisticated understanding within a subject area” (Achieve, 2015, p. 3). Learning progressions are typically models of student learning over an extended amount of time, often several years (Lehrer & Schauble, 2015). However, the PLiE model presented here is intended to provide teachers with a sharper understanding of how sub-concepts may be related and how they may build upon each other.

Note. The dimensions of literacy are based on the following works: International Technology Education Association (1996); National Academy of Engineering & National Research Council (2002, 2006); and A framework for K-12 science education: Practices, crosscutting concepts, and core ideas (2012). The big ideas are synthesized from the following works: Carr et al. (2009, p. 101); Merrill et al. (2009); National Academy of Engineering (2009, pp. 151–152; 2010, pp. 35–36); Sneider & Rosen (2009, p. 131). The engineering habits of mind definitions are provided by the National Academy of Engineering (2018) LinkEngineering Educator’s Exchange. The concepts for the Engineering Knowledge and Engineering Practice dimensions emerged from this study. In addition, the results of this study included sub-concepts for each concept, which are not provided in this table, to support the scaffolding of engineering instruction.
other in order to influence more immediate and purposeful instructional practice. The goal is to help teachers think through novel concepts in engineering to improve their instruction from day to day or week to week. Accordingly, the template in Figure 6 was developed based on the five characteristics of learning progression frameworks by Magana (2017). Then, following the consultation with a variety of engineering education experts, including teachers, professors, and industrial practitioners, sample progressions of learning for each of the concepts from the emerging taxonomy were drafted. In Figure 7, a sample draft for the concept of Problem Framing is provided. While these sample PLiEs can indicate how to scaffold progress across different depths of student understanding, from basic to advanced, the authors realize that learning can and will be shaped according to the individualities of students and their communities. Similar to science education, PLiEs must be empirically grounded, testable, and hold true for different learners in various instructional settings (Corcoran, Mosher, & Rogat, 2009; Duncan & Hmelo Silver, 2009). Therefore, the hope is that the initial development will spur the refinement and expansion of PLiEs within and possibly beyond the scope presented in this paper.

Research Recommendations

As development continues, on-going research is necessary to validate the efficacy of the taxonomy and of each progression of learning as it relates to varying demographics, grade levels, and cognitive abilities. For example, although the progressions of learning can provide stepping stones among and between concepts and sub-concepts, as they are implemented, focused research will be needed to understand the major and minor changes teachers make between the varying levels. This will ensure that appropriate revisions are made with consideration of pedagogical and learning approaches. Additionally, although participants from a variety of backgrounds and areas of expertise convened to inform the perception of what students should know through developmentally appropriate instruction, next phases of research should be focused on students’ cognitive and emotional abilities. Some future areas of inquiry, originally recommended by the National Academy of Engineering (2010, p. 3), include:

- How do children in formal educational settings come to understand (or misunderstand) core concepts and apply (or misapply) skills in engineering?
- What are the most effective ways of introducing and sequencing engineering concepts, skills, and ways of thinking for learners at the high-school level?
- What are the most important synergies in the learning and teaching of engineering along with mathematics, science, technology, and other subjects?
- What are the most important considerations in designing materials, programs, assessments, and educator professional development that engage all learners, including those historically underrepresented in engineering?
- How may a conceptual framework for the study of engineering inform the creation of P-12 engineering education standards?
<table>
<thead>
<tr>
<th>Level 4</th>
<th>I can successfully (Engineering Habit) (Engineering Context) through application of (Concept). (Performance Task)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Performance Task:</strong> Indicator of mastery understanding by applying core concept knowledge through engineering skillsets and habits of mind.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub-Concept #1</th>
<th>Sub-Concept #2</th>
<th>Sub-Concept #3</th>
<th>Sub-Concept #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>I can...</td>
<td>I can...</td>
<td>I can...</td>
<td>I can...</td>
</tr>
<tr>
<td>(Advanced)</td>
<td>(Advanced)</td>
<td>(Advanced)</td>
<td>(Advanced)</td>
</tr>
<tr>
<td>Advanced Level (3): Demonstrating competency over challenging subject matter, including subject-matter knowledge, application of such knowledge to real-world situations, and analytical skills appropriate to the subject matter.</td>
<td>Advanced Level (3): Demonstrating competency over challenging subject matter, including subject-matter knowledge, application of such knowledge to real-world situations, and analytical skills appropriate to the subject matter.</td>
<td>Advanced Level (3): Demonstrating competency over challenging subject matter, including subject-matter knowledge, application of such knowledge to real-world situations, and analytical skills appropriate to the subject matter.</td>
<td>Advanced Level (3): Demonstrating competency over challenging subject matter, including subject-matter knowledge, application of such knowledge to real-world situations, and analytical skills appropriate to the subject matter.</td>
</tr>
<tr>
<td>Level 3</td>
<td>Level 3</td>
<td>Level 3</td>
<td>Level 3</td>
</tr>
<tr>
<td>(Proficient)</td>
<td>(Proficient)</td>
<td>(Proficient)</td>
<td>(Proficient)</td>
</tr>
<tr>
<td>Level 2</td>
<td>Level 2</td>
<td>Level 2</td>
<td>Level 2</td>
</tr>
<tr>
<td>(Basic)</td>
<td>(Basic)</td>
<td>(Basic)</td>
<td>(Basic)</td>
</tr>
<tr>
<td>Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.</td>
<td>Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.</td>
<td>Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.</td>
<td>Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.</td>
</tr>
<tr>
<td>Level 1</td>
<td>Level 1</td>
<td>Level 1</td>
<td>Level 1</td>
</tr>
</tbody>
</table>

*Figure 6. Progression of Learning in Engineering (PLiE) template.*
**Engineering Dimension:** Engineering Practices  

**Engineering Practice:** Engineering Design  

**Core Concept:** Problem Framing  

**Overview:** Problem Framing is a process, which occurs early in and throughout the practice of Engineering Design, that involves outlining one’s mental interpretation of a problem situation by identifying the goals and essential issues related to developing a desired solution. This includes identifying design parameters to formulate a problem statement that (a) considers multiple perspectives, (b) removes perceived assumptions that unnecessarily limit the problem-solving process, and (c) frames the design scenario in such a manner that helps guide the problem-solving process. This core concept is important to the practice of Engineering Design as design problems are, by nature, ill-structured and open-ended.

<table>
<thead>
<tr>
<th>Level</th>
<th>Identifying Design Parameters</th>
<th>Problem Statement Development</th>
<th>Considering Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 4</td>
<td>I can successfully construct justified problem statements that highlight the key elements of a design scenario, including multiple perspectives (incorporating the clients/end-users), to guide the evaluation of trade-offs between multiple, and sometimes conflicting, goals, criteria, and constraints during a design project. <em>(Performance Task)</em></td>
<td>Level 3</td>
<td>I can evaluate a problem statement to determine if a vision for a design team is clearly stated with sufficient information that justifies the execution of a problem-solving process. <em>(Advanced)</em></td>
</tr>
<tr>
<td>Level 3</td>
<td>I can evaluate the relationships between design criteria and constraints to prioritize them within a specific context of design in order to effectively balance trade-offs between any conflicting goals. <em>(Advanced)</em></td>
<td>Level 3</td>
<td>I can summarize the key elements of a design situation to write a concise problem statement that represents a clear description of a justifiable issue along with the main goal(s) to be addressed by the problem-solving team. <em>(Proficient)</em></td>
</tr>
<tr>
<td>Level 2</td>
<td>I can infer design criteria and constraints that are not explicitly described in a provided description of a design situation. <em>(Proficient)</em></td>
<td>Level 1</td>
<td>I can identify the key elements of a design situation which includes “what the central issue is that requires a resolution”, “who the issue affects”, “when/where the issue occurs”, and “why the issue needs a novel solution”. <em>(Basic)</em></td>
</tr>
<tr>
<td>Level 1</td>
<td>I can analyze a provided description of design situation to identify explicit design criteria and constraints. <em>(Basic)</em></td>
<td>Level 1</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 7. Sample Progression of Learning in Engineering (PLiE) for the concept of problem framing (Kim, Newman, Lastova, Bosman, & Strimel, 2018).*
Conclusion

As multiple reports have concluded, a lack of epistemological foundation for engineering at the P-12 level can be one of the factors hindering students’ coherent and consistent study in engineering. Specifically, the ability of teachers to successfully design, align, and assess instructional tasks is dependent upon the creation and validation of a framework of engineering concepts and practices, which have been supported by research and vetted by professionals from a variety of backgrounds. Therefore, the authors of this study reviewed the literature on P-12 engineering education and conducted an investigation to establish a taxonomy of engineering concepts deemed potentially appropriate for secondary learners in an effort to set the epistemic basis for the school subject. To achieve this task, a modified Delphi study was enacted that involved various experts in the process of identifying and agreeing on engineering concepts. The result of this study implies that the defined dimensions of engineering literacy (see Table 9) and content taxonomy can support educators in establishing a clearer vision and roadmap for designing and developing curricula and instruction for P-12 engineering education. This would involve scaffolding instruction that builds from explicitly developing engineering habits at a young age to teaching in-depth concepts to inform engineering practice in high school (see Figure 2). While continued research is necessary, the authors hope that this work can help further define engineering literacy, set a foundation for developing progressions of learning in P-12 engineering, and open more conversations about engineering as a compulsory school subject. Through these conversations, it will be exciting to see what the engineering and education communities can develop to ensure that every child has the opportunity to learn, think, and act like an engineer.

Author Bios

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References


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Appendix A

Concept Discovery Questionnaire

The overall intent of this study is to provide educators with the primary components of a viable engineering taxonomic structure for secondary technology and engineering programs. Specifically, this study will seek to establish (1) core concepts and (2) sub-concepts for the development of learning progressions to support the coherent study of engineering within secondary technology and engineering education classrooms. You have received this invitation because you have been identified or nominated as an expert in secondary/postsecondary engineering education with experience in the engineering or engineering technology professions. The engineering content being sought in this study is intended for use in the future development of a curriculum framework for students at the high school level.

If you agree to participate in this research study, you will be expected to serve as a panel expert for a three-round Delphi study. The Delphi technique attempts to build a consensus of opinion by asking experts a round of questions, developing more refined questions that are fed back to the respondents, and so on. After each round of questions, the research team will synthesize the results and return these results in the subsequent Delphi round to allow each participant to refine the results and indicate their agreement with the information that has been established.

- **Round 1:** focused on concept discovery (identifying core concepts and sub-concepts in both the technical and fundamental content areas of engineering)
- **Round 2:** focused on concept prioritization
- **Round 3:** focused on concept rating

Member checking of the final results will take place in a symposium setting. Throughout this process, no identifiable information about each expert will be collected in connection with the responses.

Delphi Round #1

Thank you for your participation in the first Delphi round to identify the core concepts and corresponding sub-concepts for the secondary study of engineering. The following diagram depicts the hierarchical structure for the engineering content knowledge. It shows the relative positions of the taxonomy divisions. This visual aid is provided to more clearly convey to panel members the approach to identifying unique knowledge areas of secondary engineering.

A key feature of this taxonomy is the content knowledge elements in addition to the fundamental practices of engineering literacy. Several attempts have been made to identify and define the general and broad set of fundamental elements of engineering or the nature of engineering (e.g., designing solutions to ill-defined problems, considering impacts, balancing trade-offs, modeling, etc.). See Supporting Literature #1. However, this project also seeks to identify the specific technical content to support the analytical and practical skills exclusive to engineering. While some of the core concepts that you will identify in these content areas may be considered science or mathematics, it is the context and application of these concepts in engineering that will differentiate the study of the technical elements from other school subjects.

The term “content area” was purposefully selected for use in this taxonomy. The selected content areas should not be viewed as engineering career disciplines but organizers for concepts that will support the development of engineering literacy at the secondary level and prepare students for success in any engineering major if they decide to do so. The four content areas (Mechanical, Electrical, Civil, and Chemical) were selected as the areas for organizing the technical elements of secondary engineering as these areas can be viewed as the foundations of any engineering career discipline. For example, one can view computer engineering having roots in electrical, aerospace engineering having roots in mechanical, environmental engineering having roots in civil, etc. A key piece of literature supporting these content areas can be found at Supporting Literature #2 on page 27. Now, based on the information provided, use your knowledge and expertise in the field of engineering and technology education to answer the following questions.
Engineering Knowledge

Content Area: Mechanical

1. What are the main core concepts you feel represent the technical content of the mechanical engineering content area? (Support for identifying these core concepts can be found at Fundamentals of Engineering Exam, National Academies Taxonomy, or Engineering Majors) (Be as succinct as possible. Limit to 8)
   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept...

2. Under each of your designated core concepts for the content area of mechanical engineering, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)
   1. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
   2. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2

Content Area: Electrical

1. What are the main core concepts you feel represent the technical content of the electrical engineering content area? (Support for identifying these core concepts can be found at Fundamentals of Engineering Exam, National Academies Taxonomy, or Engineering Majors) (Be as succinct as possible. Limit to 8)
   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept...

2. Under each of your designated core concepts for the content area of electrical engineering, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)
   1. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
   2. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2

Content Area: Civil

1. What are the main core concepts you feel represent the technical content of the civil engineering content area? (Support for identifying these core concepts can be found at Fundamentals of Engineering Exam, National Academies Taxonomy, or Engineering Majors) (Be as succinct as possible. Limit to 8)
1. Core Concept 1
2. Core Concept 2
3. Core Concept…

2. Under each of your designated core concepts for the content area of civil engineering, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)

1. Core Concept 1
   a. Sub Concept 1
   b. Sub Concept 2
2. Core Concept 1
   a. Sub Concept 1
   b. Sub Concept 2

Content Area: Chemical

1. What are the main core concepts you feel represent the technical content of the chemical engineering content area? (Support for identifying these core concepts can be found at Fundamentals of Engineering Exam, National Academies Taxonomy, or Engineering Majors) (Be as succinct as possible. Limit to 8)

   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept…

2. Under each of your designated core concepts for the content area of chemical engineering, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)

   1. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
   2. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2

Engineering Practices

The fundamental elements of engineering education have been divided into four content areas based on the previous literature on the nature of engineering. This literature also supports the identification of the core concepts and sub-concepts for each content area. Please review the following literature as needed:

- Delivering Engineering Content in Technology Education
- Engineering in K-12 Education
- Standards for K-12 Engineering Education? (See pages 35 & 36)
- Core Engineering Concepts (Page 37)
- A Framework for Quality K-12 Engineering Education: Research and Development
- The Engineering of Technology Education

http://dx.doi.org/10.7771/2157-9288.1232
Content Area: Engineering Design

1. What are the main core concepts you feel represent the fundamental content of the engineering design content area? (Be as succinct as possible. Limit to 8)
   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept...

2. Under each of your designated core concepts for the content area of engineering design, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)
   1. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
   2. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2

Content Area: Quantitative Analysis

1. What are the main core concepts you feel represent the fundamental content of the quantitative analysis content area? (Be as succinct as possible. Limit to 8)
   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept...

2. Under each of your designated core concepts for the content area of quantitative analysis, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)
   1. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
   2. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2

Content Area: Society & Ethics

1. What are the main core concepts you feel represent the fundamental content of the society & ethics content area? (Be as succinct as possible. Limit to 8)
   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept...

2. Under each of your designated core concepts for the content area of society & ethics, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)
   1. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
   2. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
Content Area: Material Processing

1. What are the main core concepts you feel represent the fundamental content of the material processing content area? (Be as succinct as possible. Limit to 8)
   1. Core Concept 1
   2. Core Concept 2
   3. Core Concept...

2. Under each of your designated core concepts for the content area of material processing, what sub-concepts (content subdivisions) could each concept be broken into as the next level in structural hierarchy? (There is no limit to sub-concepts but try to be succinct)
   1. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2
   2. Core Concept 1
      a. Sub Concept 1
      b. Sub Concept 2

Final Comments

1. Please use the following space to provide any additional feedback on the content areas that have been identified for this taxonomy. Add a justification or clarification for any suggested modifications to the taxonomy. This feedback will be used to make final edits to each item.
## Appendix B

### Results from Rounds 2 and 3 of the Delphi Study

#### Mechanical: Rating from Rounds 2 and 3

<table>
<thead>
<tr>
<th>Core and Sub-Concept</th>
<th>Round 2 Mean</th>
<th>Round 2 SD</th>
<th>Round 3 Mean</th>
<th>Round 3 SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanics of Materials</td>
<td>4.79</td>
<td>0.77</td>
<td>4.59</td>
<td>0.60</td>
</tr>
<tr>
<td> Stress type (axial, bending, torsion, shear) and transformations</td>
<td>4.74</td>
<td>0.91</td>
<td>4.71</td>
<td>0.75</td>
</tr>
<tr>
<td> Solid mechanics (metals, plastics, woods, composites, alloys, ceramics, natural materials)</td>
<td>4.26</td>
<td>0.91</td>
<td>4.47</td>
<td>0.70</td>
</tr>
<tr>
<td> Stress-strain analysis (stress-strain diagrams; shear and moment diagrams)</td>
<td>4.37</td>
<td>0.74</td>
<td>4.24</td>
<td>0.88</td>
</tr>
<tr>
<td> Static equilibrium</td>
<td>4.32</td>
<td>1.26</td>
<td>4.18</td>
<td>1.10</td>
</tr>
<tr>
<td> Material deformations</td>
<td>3.58</td>
<td>1.04</td>
<td>3.47</td>
<td>0.70</td>
</tr>
<tr>
<td> Combined loading</td>
<td>3.79</td>
<td>0.83</td>
<td>3.29</td>
<td>0.75</td>
</tr>
<tr>
<td> Tribology (principles of friction, lubrication, and wear)</td>
<td>3.47</td>
<td>1.31</td>
<td>3.18</td>
<td>0.92</td>
</tr>
<tr>
<td> Material equations</td>
<td>3.32</td>
<td>1.03</td>
<td>3.18</td>
<td>1.10</td>
</tr>
<tr>
<td> Phase diagrams and transformation</td>
<td>3.11</td>
<td>0.72</td>
<td>3.18</td>
<td>0.92</td>
</tr>
<tr>
<td> Heat treating</td>
<td>3.21</td>
<td>0.95</td>
<td>3.00</td>
<td>0.69</td>
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<td>Dynamics and Vibrations</td>
<td>4.16</td>
<td>0.81</td>
<td>4.00</td>
<td>0.84</td>
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<tr>
<td> Scalars, vectors, resistance, gears</td>
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<td>0.93</td>
<td>4.59</td>
<td>0.97</td>
</tr>
<tr>
<td> Newton’s second law for particles and rigid bodies</td>
<td>4.00</td>
<td>1.08</td>
<td>4.12</td>
<td>0.68</td>
</tr>
<tr>
<td> Work-energy of particles and rigid bodies</td>
<td>3.79</td>
<td>0.77</td>
<td>3.94</td>
<td>1.26</td>
</tr>
<tr>
<td> Kinematics of mechanisms</td>
<td>3.74</td>
<td>0.85</td>
<td>3.59</td>
<td>0.77</td>
</tr>
<tr>
<td> Impulse-momentum of particles and rigid bodies</td>
<td>3.63</td>
<td>0.93</td>
<td>3.59</td>
<td>0.91</td>
</tr>
<tr>
<td> Kinematics of particles and rigid bodies</td>
<td>3.63</td>
<td>1.04</td>
<td>3.47</td>
<td>0.85</td>
</tr>
<tr>
<td>Mechanical Design</td>
<td>5.00</td>
<td>0.73</td>
<td>5.18</td>
<td>0.62</td>
</tr>
<tr>
<td> Manufacturing processes</td>
<td>4.63</td>
<td>0.74</td>
<td>4.65</td>
<td>0.76</td>
</tr>
<tr>
<td> Machine elements (springs, pressure vessels, beams, piping, cams and gears, threads and fasteners, power transmission, electromechanical components)</td>
<td>4.95</td>
<td>0.83</td>
<td>4.53</td>
<td>0.98</td>
</tr>
<tr>
<td> Machine control</td>
<td>4.37</td>
<td>0.58</td>
<td>4.12</td>
<td>0.90</td>
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<td>Electro-mechanical Systems</td>
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<td>0.89</td>
<td>4.47</td>
<td>0.70</td>
</tr>
<tr>
<td> Basic electricity (voltage, current, resistance, power, AC and DC)</td>
<td>5.32</td>
<td>0.92</td>
<td>5.53</td>
<td>0.61</td>
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<tr>
<td> Circuits (series and parallel, Ohm’s law, Kirchhoff’s law)</td>
<td>5.11</td>
<td>0.85</td>
<td>5.41</td>
<td>0.60</td>
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<tr>
<td> Motors and generators (induction)</td>
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<td>0.85</td>
<td>4.82</td>
<td>1.04</td>
</tr>
<tr>
<td> Charge</td>
<td>4.53</td>
<td>0.88</td>
<td>4.65</td>
<td>0.97</td>
</tr>
<tr>
<td> Magnetism</td>
<td>4.68</td>
<td>1.13</td>
<td>4.59</td>
<td>0.91</td>
</tr>
<tr>
<td>Emerging Mechanical Engineering</td>
<td>4.16</td>
<td>1.09</td>
<td>4.12</td>
<td>0.90</td>
</tr>
<tr>
<td> Mechatronics (robotics)</td>
<td>4.26</td>
<td>1.02</td>
<td>4.65</td>
<td>1.03</td>
</tr>
<tr>
<td> Bio-mechanical engineering</td>
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<td>1.02</td>
<td>4.24</td>
<td>0.88</td>
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<tr>
<td> Nanotechnology</td>
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<td>1.10</td>
<td>4.12</td>
<td>0.83</td>
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<tr>
<td> Ocean engineering</td>
<td>3.42</td>
<td>1.04</td>
<td>3.35</td>
<td>0.90</td>
</tr>
<tr>
<td>Fluid Mechanics</td>
<td>4.68</td>
<td>0.80</td>
<td>4.76</td>
<td>0.81</td>
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<tr>
<td> Fluid properties</td>
<td>4.58</td>
<td>0.75</td>
<td>4.65</td>
<td>0.59</td>
</tr>
<tr>
<td> Lift, drag, and fluid resistance</td>
<td>4.58</td>
<td>0.82</td>
<td>4.47</td>
<td>0.78</td>
</tr>
<tr>
<td> Fluid statics and motion</td>
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<td>0.86</td>
<td>4.24</td>
<td>0.81</td>
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<tr>
<td> Hydraulics</td>
<td>4.42</td>
<td>1.04</td>
<td>4.18</td>
<td>1.10</td>
</tr>
<tr>
<td> Pneumatics</td>
<td>4.42</td>
<td>1.04</td>
<td>4.12</td>
<td>1.13</td>
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<tr>
<td> Compressible and incompressible flow</td>
<td>4.05</td>
<td>1.00</td>
<td>4.06</td>
<td>0.73</td>
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<td> Computational fluid mechanics</td>
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<td>0.93</td>
<td>3.47</td>
<td>0.98</td>
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<td>Thermodynamics</td>
<td>4.53</td>
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<td>4.24</td>
<td>1.00</td>
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<tr>
<td> Thermodynamic properties, laws, and processes</td>
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<td>0.86</td>
<td>4.29</td>
<td>1.02</td>
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<td> Energy transfers</td>
<td>4.63</td>
<td>0.93</td>
<td>4.24</td>
<td>0.94</td>
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<tr>
<td> Equilibrium</td>
<td>4.26</td>
<td>1.16</td>
<td>4.18</td>
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<tr>
<td> Thermal resistance</td>
<td>3.95</td>
<td>0.83</td>
<td>3.88</td>
<td>0.83</td>
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<td> Gas properties</td>
<td>4.53</td>
<td>1.23</td>
<td>3.82</td>
<td>0.86</td>
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<tr>
<td> Power cycles and efficiency</td>
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<td>1.06</td>
<td>3.71</td>
<td>1.07</td>
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<td> Heat exchangers</td>
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<td>0.76</td>
<td>3.65</td>
<td>0.78</td>
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<td> HVAC processes</td>
<td>3.21</td>
<td>1.06</td>
<td>3.18</td>
<td>0.92</td>
</tr>
</tbody>
</table>

*Note.* The rating scale: 1 through 6.
### Electrical: Rating from Rounds 2 and 3

<table>
<thead>
<tr>
<th>Core and Sub-Concept</th>
<th>Round 2</th>
<th></th>
<th>Round 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical Power</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Force</td>
<td>4.83</td>
<td>1.07</td>
<td>5.12</td>
<td>0.68</td>
</tr>
<tr>
<td>• Motors and generators</td>
<td>4.67</td>
<td>1.05</td>
<td>5.00</td>
<td>0.59</td>
</tr>
<tr>
<td>• Electrical materials (chemical, mechanical, thermal)</td>
<td>4.61</td>
<td>0.89</td>
<td>4.71</td>
<td>0.96</td>
</tr>
<tr>
<td>• Electro-magnetics</td>
<td>4.28</td>
<td>0.80</td>
<td>4.65</td>
<td>0.76</td>
</tr>
<tr>
<td>• Transformers</td>
<td>4.56</td>
<td>0.83</td>
<td>4.41</td>
<td>1.09</td>
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<td>• Voltage regulation</td>
<td>4.28</td>
<td>0.87</td>
<td>4.06</td>
<td>0.73</td>
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<td>• Transmission and distribution</td>
<td>4.22</td>
<td>1.18</td>
<td>3.94</td>
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<td>• Single and three-phase AC power</td>
<td>4.06</td>
<td>0.97</td>
<td>3.88</td>
<td>0.96</td>
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<td>• Maxwell equations</td>
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<td>3.76</td>
<td>0.94</td>
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<td><strong>Circuit Analysis</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>• Current, voltage, charge, energy, and power</td>
<td>5.00</td>
<td>0.82</td>
<td>5.24</td>
<td>0.55</td>
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<tr>
<td>• Series and parallel equivalent circuits</td>
<td>5.11</td>
<td>0.87</td>
<td>5.29</td>
<td>0.57</td>
</tr>
<tr>
<td>• Ohm’s law and Kirchhoff’s laws</td>
<td>5.11</td>
<td>0.94</td>
<td>5.00</td>
<td>0.69</td>
</tr>
<tr>
<td>• Power and energy</td>
<td>5.00</td>
<td>0.88</td>
<td>4.94</td>
<td>0.64</td>
</tr>
<tr>
<td>• Impedance, capacitance, and inductance</td>
<td>4.22</td>
<td>1.13</td>
<td>4.59</td>
<td>0.77</td>
</tr>
<tr>
<td>• Wave forms</td>
<td>4.06</td>
<td>0.97</td>
<td>4.06</td>
<td>0.64</td>
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<tr>
<td>• Node and loop</td>
<td>4.28</td>
<td>1.19</td>
<td>3.88</td>
<td>0.68</td>
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<tr>
<td><strong>Electronics</strong></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>• Instrumentation</td>
<td>4.72</td>
<td>0.87</td>
<td>4.94</td>
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<tr>
<td>• Semiconductor</td>
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<td>0.82</td>
<td>4.35</td>
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<tr>
<td>• Amplifiers</td>
<td>4.11</td>
<td>0.87</td>
<td>4.29</td>
<td>0.75</td>
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<tr>
<td>• Solid state fundamentals</td>
<td>4.11</td>
<td>0.81</td>
<td>3.94</td>
<td>0.80</td>
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<td>• Discrete devices</td>
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<td>0.85</td>
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<tr>
<td><strong>Control Systems</strong></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>• Sensors</td>
<td>4.67</td>
<td>1.00</td>
<td>4.65</td>
<td>0.68</td>
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<td>• Closed and open loop</td>
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<td>0.97</td>
<td>4.94</td>
<td>0.87</td>
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<td>• Feedback systems</td>
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<td>1.08</td>
<td>4.82</td>
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<tr>
<td>• Block diagramming</td>
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<td>1.17</td>
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<tr>
<td>• System response</td>
<td>4.33</td>
<td>1.15</td>
<td>4.35</td>
<td>0.90</td>
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<tr>
<td>• System performance</td>
<td>4.56</td>
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http://dx.doi.org/10.7771/2157-9288.1232
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*Note.* The rating scale: 1 through 6.
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**Note.** The rating scale: 1 through 6.
## Chemical: Rating from Rounds 2 and 3

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## Quantitative Analysis: Rating from Rounds 2 and 3

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Note. The rating scale: 1 through 6.
## Society and Ethics: Rating from Rounds 2 and 3

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*Note.* The rating scale: 1 through 6.
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