Towards a Framework for P-12 Engineering Learning

White Paper from the Advancing Excellence in P12 Engineering Education Research Collaborative

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Forward

Engineering: A National Imperative

Our world is full of seemingly insurmountable challenges; making solar energy economical, providing access to clean water, engineering better medicines, and securing cyberspace to name a few. Historically, engineering has solved the world's most daunting problems. Paramount to these challenges, is the need to prepare the next generation of engineering-literate global citizens to solve issues of the ensuing century. While the demands of our world require creative, capable, and diverse problem solvers, young learners have limited opportunities to engage in engineering as a deliberate, and cross-curricular component of their typical school day.

Many school systems have turned to science, technology, engineering, and mathematics (STEM) education to answer this call. STEM has subsequently become a nationally, recognized "buzz word" in education, spurring renewed excitement and engagement in robotics, science fairs, and coding. While a promising and progressive response, these surface-level experiences are too often the exception in education rather than the standard, and still not to the depth needed in training a prepared populace for the coming future. For example, STEM education in many communities is a fun reprieve from "education (business) as usual" and is not often positioned as a long-lasting educational transformation. Some educational organizations may even just rebrand science, technology, and/or mathematics programs with a veneer of STEM education without adhering to transdisciplinary practices championed by STEM education experts.

This is not to say that all STEM education programs fall into this category. There are, in fact, several high-quality STEM programs and curriculum throughout the country that remain committed to integrative, inquiry-driven, and design/problem-based classroom experiences. However, the inherent broadness of a term like "STEM," allows for the adoption of diluted imitations. This dilution of STEM education from a national perspective prohibits its ability to enact transformative change, and prepare the citizens needed to solve the evolving societal challenges. This unacknowledged truth is detrimental to our regional, national, and global success and the promise of an informed and participating citizenship.

Engineering, however, does not share many of the potential drawbacks of STEM education. For example, engineering is a defined discipline with a millennium of advancement, application, refinement, and post-secondary training and expertise. Engineering is naturally integrative, calling upon scientific knowledge, mathematical truths, and technological capabilities to design solutions to societal, economic, and environmental problems. Design, one of the core practices of engineering, can also be leveraged by educators to create approachable, yet authentic contexts for student learning. Put simply, engineering is uniquely positioned to support transdisciplinary learning experiences that foster rich connections to knowledge and skills of academic disciplines. If implemented with fidelity and resolution, engineering education is poised to deliver on many of the promises of STEM education. Accordingly, we must advocate for all students to engage in engineering in order to meet the most difficult challenges of the future.

Such a formidable initiative thrusts forward political and economic trials of its own. Budget constraints, space in the current school schedule, and teacher professional development all influence educational practice. Also, as engineering is a novel, yet emerging trend in schools, it lacks validated common expectations, classroom practices, teacher training, and curriculum. But, even with the obstacles of implementation, the last decade has seen the proliferation of engineering in U.S. elementary, middle, and high schools. Science education leaders have acknowledged and positioned engineering as a vehicle for, and a complement to, science learning. The technology education community evolved with a name change of its professional organization to the International Technology (and Engineering) Educators Association (ITEEA). Moreover, the 2017 Phi Delta Kappa poll of the public's attitudes toward schools reported that Americans overwhelmingly (82%) view technology and engineering education as an important indicator of school quality.

While it is true that millions of students participate in formal P-12 engineering coursework, 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. However, the authors hope that this framework can serve as a cohesive, yet dynamic guide, for defining engineering learning for students. Moreover, the authors hope that such consistency can 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 framework can ultimately help set the foundation for the development of learning progressions and/or standards to support establishing coherent educational pathways in engineering.

Summary

While current initiatives in P-12 engineering education are promising, a clear vision for how to articulate P-12 engineering programs or learning initiatives to best contribute to the general literacy of our children has eluded educators, administrators, and curriculum developers. Consequently, the *Framework for P-12 Engineering Learning* has been developed, through years of research and stakeholder engagement, to foster an engineering learning community with a shared focus, vision, and research agenda to ensure that every child is given the opportunity to think, learn, and act like an engineer. The goal of this framework is to provide a cohesive, yet dynamic guide, for defining engineering learning for students and establishing the building blocks to set the foundation for a coherent approach for states, school systems, and other organizations to develop engineering learning progressions, standards, curriculum, instruction, assessment, and professional development to better democratize engineering education across grades P-12. A coherent and consistent approach throughout grades P-12 is key to realizing the vision for engineering learning embodied in this framework and ensuring that all students, over multiple years of school, have the opportunity to orient their ways of thinking through developing engineering habits of mind, cultivate their skills by actively engaging in engineering practices, and inform their practices through the appropriate application of engineering concepts that are scientific, mathematical, and technical in nature.

While this framework does not specify grade bands for the habits, practices, and concepts of engineering, it does provide endpoints or the destination for each component idea that describes the student understandings that should be acquired by the end of secondary school. Moreover, the details for each of these elements can provide the content necessary for creating a roadmap or progressions of learning toward achieving engineering literacy. This comes at a time when our world requires, more than ever, creative, capable, and diverse problem solvers proficient in the concepts and practices of engineering. In addition, under the umbrella of engineering learning, teachers can use this framework to not only prepare all students to be better problem solvers but also prepare those who are interested in entering a career/trades/vocational pathway or pursuing post-secondary education toward engineering-related careers. As a result, this framework aims to enhance the rigor, depth, and coherency of engineering concepts that are addressed in P-12 classrooms and do so in a manner that strives to achieve equity in engineering for all students.

In order to help guide P-12 program development, this framework provides the following definitions in regards to engineering learning:

Engineering Literacy is the confluence of content knowledge, habits, and practices merged with the ability to read, write, listen, speak, think, and perform in a way that is meaningful within the context of engineering and the human-made world. *Engineering Literacy* is achieved through *Engineering Learning*.

Engineering Learning is three-dimensional (Figure 1) and focuses on the *Engineering Habits of Mind* (e.g. Optimism, Persistence, Creativity) that students should develop over time through repetition and conditioning, *Engineering Practices* (Engineering Design, Materials Processing, Quantitative Analysis, and Professionalism) in which students should become competent, and *Engineering Knowledge* (Engineering Sciences, Engineering Mathematics, and Technical Applications) that students should be able to recognize and access to inform their *Engineering Practic*e. The goal of *Engineering Learning* is to foster *Engineering Literate Students*.

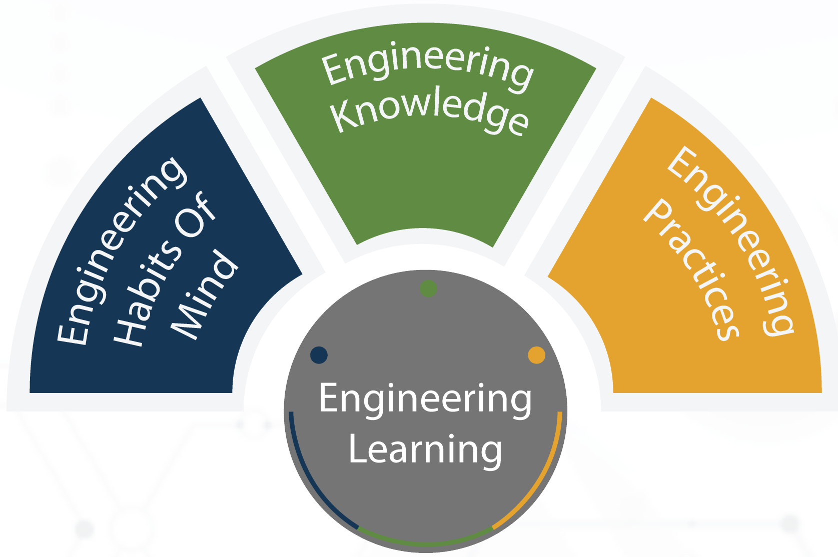


Figure 1: Dimensions of Engineering Learning

An **Engineering Literate Student** is an integrated learner who has oriented their way of thinking, by developing the *Engineering Habits of Mind*, to (a) recognize and appreciate the influence of engineering on society and society on engineering, (b) responsibly, appropriately, and optimally enact *Engineering Practices*, whether independently or in teams, within personal, social, and cultural situations, and (c) address technological issues, under specified constraints, with an appropriate understanding of engineering concepts—that are scientific, mathematical, and technical in nature.

The **Goal of Engineering Literacy for All** is to ensure that every student, regardless of their race, gender, ability, socioeconomic status, or career interests, has the opportunity to engage in three-dimensional *Engineering Learning* to cultivate their *Engineering Literacy* and become informed citizens who are capable of adapting to, and thriving in, the workplace and society of the future. *Engineering Literacy* is not only relevant to individuals but also to communities and society as a whole. Furthermore, research suggests that increasing opportunities for *all* students can improve the diversity of the workforce and improve technological and innovative output. Therefore, by the end of secondary school all students should be provided the learning experiences necessary to (1) orient their ways of thinking by developing *Engineering Habits of Mind*, (2) be able to competently enact the *Engineering Practices*, and (3) appreciate, acquire, and apply appropriate *Engineering Knowledge* to confront and solve the problems in which they encounter.

An **Engineering Learning Initiative or Program** is a structured sequence of three dimensional educational experiences that aims to (1) cultivate *Engineering Literacy* for all students, regardless of their career interest, (2) assist in improving students' academic and technical achievement through the integration of concepts and practices across all school subjects (e.g., science, mathematics, technology, language arts, reading), (3) enhance a student's understanding of engineering-related career pathways and, (4) set a solid foundation for those who may matriculate to a post-secondary program toward an engineering-related career.

In addition, the following principles were established to guide the development of this framework as well as the implementation of any resulting engineering teaching and learning initiatives:

Equity must Remain at the Forefront - Achieving engineering literacy for all requires that equity be at the forefront of any engineering learning initiative. Whether at the national, state, district, or school level, instruction and classroom culture should be affected by deliberate efforts to ensure equitable approaches to engineering. Therefore, any related educational initiatives resulting from the framework, must make sure there are appropriate supports provided based on individual students' needs so that all can achieve similar levels of success.

Strive for Authenticity to Engineering - While engineering concepts, habits, and practices can and should be leveraged, when appropriate, as a context for teaching and learning a variety of subjects, it is important that engineering learning is aligned to engineering as a unique discipline. Therefore, it is necessary to continually evaluate whether engineering-related instructional activities are accurately depicted to children in a manner authentic to engineering. If not, we may expose a child to something called engineering that they dislike and therefore never explore the actual field and, concurrently, we may mislead or under prepare children as we provide activities that they enjoy that have little relation to authentic engineering practice.

Focus on Depth over Breadth - Instead of providing students with broad learning objectives such as "apply the engineering design process to solve a problem," engineering concepts should be detailed to a level of specificity necessary to scaffold learning in a way that enables a student to perform engineering practices well, and with increased sophistication, along the path toward engineering literacy. This information will allow the engineering concepts to become less abstract while providing more in-depth content for engineering curriculum and instruction. This is an important principle as the problems that the world faces today, and in the future, will require innovations that are built upon knowledge that is increasingly highly specialized and deep.

Build Upon Children's Natural Problem-Solving Abilities - People are born as natural problem solvers. Children can often be seen seeking to improve their situations and environments through exploring solutions to a broad range of circumstances and problems. Through this type of exploration and play, children learn vital lessons about the world around them, specifically through the experience of failure. While problems are typically solved through general problem-solving approaches and trial-and-error methods, engineering literate individuals tend to follow a more disciplined, informed, and organized approach to solve an array of problems involving the creation of products and systems. Accordingly, this framework, and any resulting educational activities, should be positioned to direct students away from a routinized or generic approach to problem solving and toward more rigorous engineering practices, beyond just design, which requires use of appropriate mathematical, technical, and science concepts in conjunction with technological tools for optimizing solutions.

Leverage Making as a Form of Active Learning - The act of making products and systems, both physical and digital, that are devised by students provides them with experiential learning that engages them in constructing their own knowledge and orients their learning within real contexts (National Academies of Sciences, Engineering, & Medicine, 2018). This type of learning can scaffold age-appropriate tool knowledge and technique that is both engaging and valuable for learning how objects are assembled and created as well as how they work. However, students often have few valuable opportunities to practice tinkering, designing, making, and testing solutions during school (Change the Equation, 2016). Therefore, this framework positions P-12 Engineering to provide learning environments for students to explore and understand the proper use of authentic tools, materials, and software through project, problem, and design-based instruction.

Connect with Student Interests, Culture, & Experiences - Connecting with student interests, culture, and experiences makes learning relevant to their world and is necessary for removing barriers toward further engineering studies and potential career pathways. Therefore, this framework was developed with attention to specific examples in which the content provided within could be aligned to student communities through socially relevant and culturally situated contexts. These applications can be one attempt to help students to build personal relationships with engineering concepts and practices and hopefully feel like engineering is more relevant to their lives. Therefore, any ways in which this framework is used for developing standards, learning progressions, and/or curriculum should intentionally model learning experiences that are contextualized in ways that are socially relevant and culturally responsive to students.

Engineering Habits of Mind

As a goal of P-12 Engineering Education, by the end of secondary school, engineering literate students should be:

- able to maintain an **optimistic** outlook throughout the course of a project in order to persevere in creating a viable solution to the presented problem.
- **persistent** throughout the course of a project in order to meet the project's objectives, uphold established deadlines, and be accountable for creating viable solutions to problems.
- **collaborative/communicative** throughout the course of a team-based project to leverage diverse perspectives in successfully completing designated tasks.
- **creative** throughout the course of a project, which should be reinforced through the repetitive use of creativity strategies and tools, in order to develop an innovative solution to a presented problem.
- **conscientious** when making decisions throughout the course of a project, which should be reinforced through repetitive questioning and design evaluations, in order to develop an ethical solution to the presented problem.
- able to think in terms of **systems** when making decisions throughout the course of a project, which should be reinforced through recurring design critiques, in order to consider how a solution idea or design interacts with, and impacts, the world.

Optimism

Optimism is the ability to look at the more favorable side of an event or to expect the best outcomes in various situations.

Systems Thinking

Systems Thinking is the ability to recognize that all technological solutions are systems of interacting elements that are also embedded within larger man-made and/or natural systems and that each component of these systems are connected and impact each other.

Collaboration

Collaboration is the ability to work with others to complete a task and achieve desired goals.

Creativity

Creativity is the ability to think in a way that is different from the norm to develop original ideas.

Conscientiousness

Conscientiousness is the ability to focus on performing one's duties well and with the awareness of the impact that their own behavior has on everything around them

Persistence

Persistence is the ability to follow through with a course of action despite of the challenges and oppositions one may encounter.

Engineering Practices

As a goal of P-12 Engineering Education, by the end of secondary school, engineering literate students should be able to demonstrate competence in the practices of Engineering. These practices are:

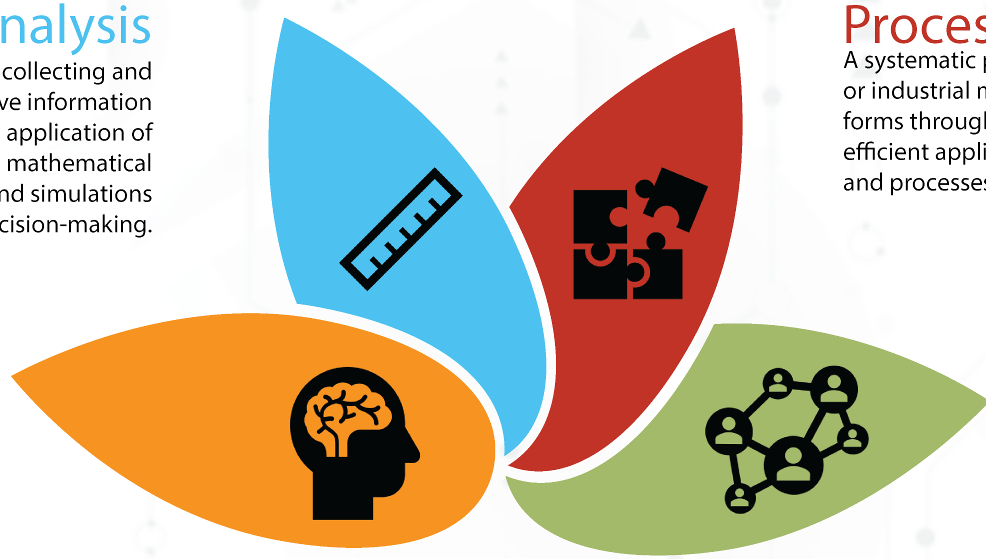
- **Engineering Design** is the practice that engineering literate individuals use to develop solutions to problems. It is defined as a systematic, intelligent process in which people generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints (Dym et al., 2005, p.104). Competency in this practice requires knowledge of core concepts such as problem framing, decision making, ideation, and prototyping.
- ***Material Processing*** is the primary practice that engineering literate individuals use to convert materials into physical products, often referred to as *making* (See *Guiding Principle #5 Making is an Active Form of Learning*). It is defined as a systematic process to transform raw or industrial materials into more valued forms through the appropriate and efficient application of tools, machines, and processes. Competency in this practice requires knowledge of core concepts such as fabrication, material classification, and safety.
- ***Quantitative Analysis*** is the primary practice that engineering literate individuals use to support, accelerate, and optimize the resolution of design problems. It is defined as a systematic process of collecting and interpreting quantitative information through the appropriate application of data analytic tools, mathematical models, computations, and simulations to inform predictive decision-making (See *Guiding Principle #1 Authenticity in Engineering*). Competency in this practice requires knowledge of core concepts such as computational thinking, computational tools, and data collection, analysis, and communication.
- ***Professionalism*** is the practice that engineering literate individuals follow to maintain the highest standards of integrity and honesty in order to be trusted by their communities to make ethical decisions that protect the public's well-being, improve society, and mitigate negative impacts on the environment. This includes the conventions associated with professional ethics, workplace behavior and operations, honoring intellectual property, and functioning within engineering-related careers. In addition, engineering *Professionalism* includes understanding the intended and unintended impacts of technology and the role society plays in technological development.

Quantitative Analysis

A systematic process of collecting and interpreting quantitative information through the appropriate application of data analytic tools, mathematical models, computations, and simulations to inform predictive decision-making.

Materials Processing

A systematic process to transform raw or industrial materials into more valued forms through the appropriate and efficient application of tools, machines, and processes.



Engineering Design

A systematic, intelligent process in which students use to generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints.

Professionalism

The practice that engineer literate individuals follow to maintain the highest standards of integrity and honesty in order to be trusted by their communities to make ethical decisions that protect the public's well-being, improve society, and mitigate negative impacts on the environment.

Engineering Knowledge

As a goal of P-12 Engineering Education, by the end of secondary school, engineering students should be able to recognize and access concepts in three broad domains of knowledge, which include (1) **Engineering Sciences**, (2) **Engineering Mathematics**, and (3) **Engineering Technical Applications***,* to inform their engineering practice.

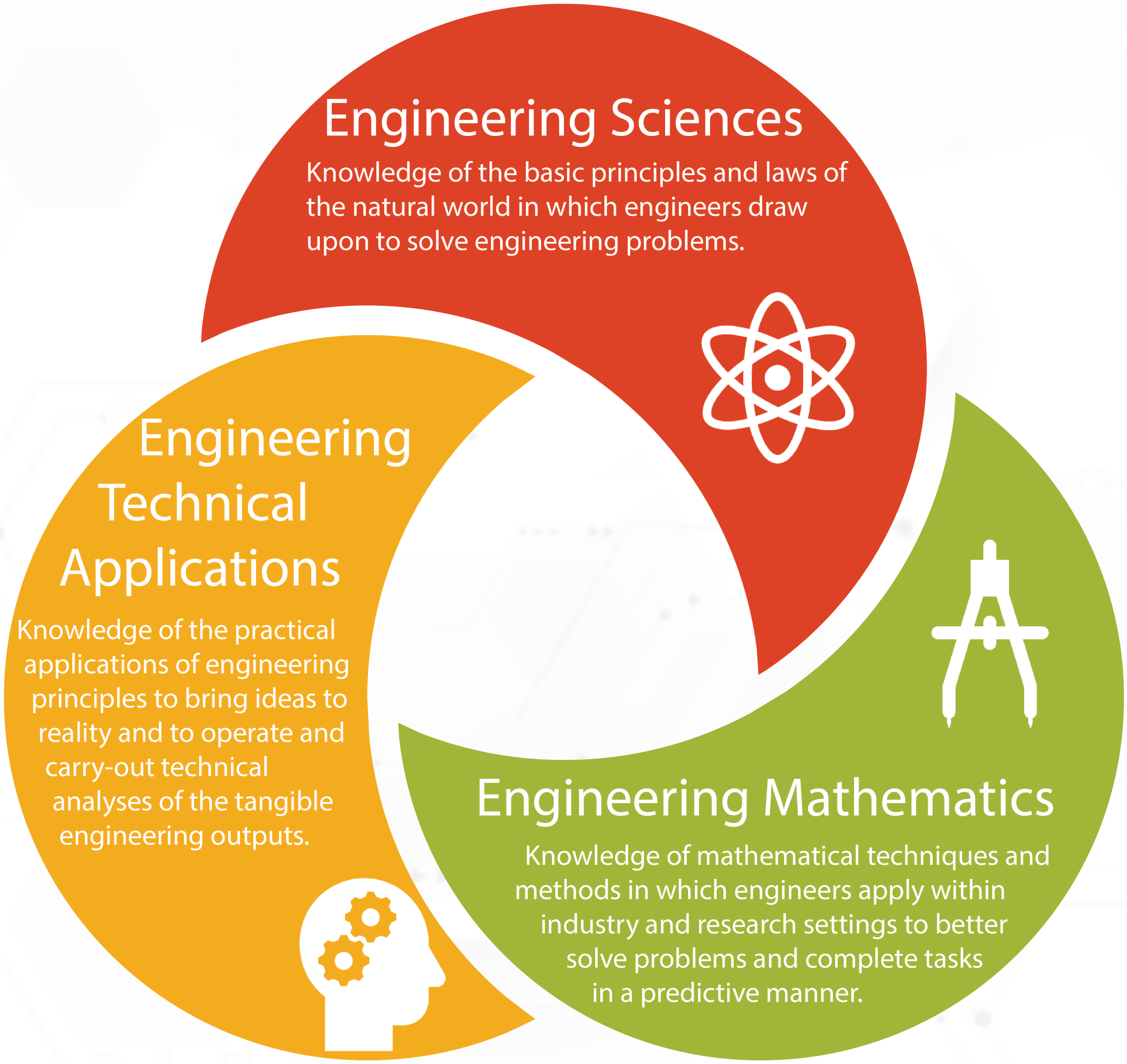
NOTE: While the concepts related to the Engineering Practices are labeled as "core" and deemed essential to achieve Engineering Literacy, it should not be expected that an engineering literate student gain knowledge of all the concepts available in the Engineering Knowledge domain. Engineering Knowledge concepts are auxiliary in nature and could be drawn upon, when appropriate to (1) help students solve problems in a manner that is analytical, predictive, repeatable, and practical, (2) situate learning in an authentic engineering context, and (3) guide the development of engineering programs.

NOTE: There may be instances when an engineering program may choose to identify and teach "auxiliary concepts" within the engineering knowledge dimension that are not listed in this document. The concepts and sub-concepts presented in this framework for engineering knowledge are derived from the Engineering Taxonomy for P-12 Engineering Programs developed by Strimel and colleagues (2020). It is expected that schools that specialize in STEM areas (e.g. biomedical, aerospace, nanotechnology) may want to expand the selection of concepts listed below. This expansion is encouraged. Programs should use the concepts and sub-concepts listed here as a starting point to align with the overall intent of this framework.

As a goal of P-12 Engineering Education, by the end of secondary school, engineering literate students should be able to recognize and, when appropriate, apply **Engineering Science** concepts to inform their engineering practice. ***Engineering Science*** is a knowledge base consisting of the basic principles and laws of the natural world in which engineering professionals draw upon to solve engineering problems. This knowledge, which may include auxiliary concepts such as *statics*, *mechanics of materials*, and *dynamics*, relies heavily on, and is inseparable from, the application of mathematics and technical knowledge. This knowledge base is essential as engineering tasks are typically open-ended and ill-defined whereas different solution approaches may draw on a student's knowledge gained from a variety of domains of knowledge.

As a goal of P-12 Engineering Education, by the end of secondary school, engineering literate students should be able to recognize and, when appropriate, apply **Engineering Mathematics** concepts to inform their engineering practice. **Engineering Mathematics** is a knowledge base consisting of practical mathematical techniques and methods in which engineering professionals apply within industry and research settings to better solve problems and complete engineering tasks in a predictive manner. This knowledge, which includes applied analysis auxiliary concepts such as *algebra*, *geometry*, *statistics and probability*, and *calculus*, is intimately tied to, and necessary for, expanding scientific and technical knowledge. The **Engineering Mathematics** knowledge base is essential as engineering tasks are typically open-ended and ill-defined whereas different solution approaches may draw on a student's knowledge gained from a variety of domains of knowledge. In the P-12 classrooms, students should engage in experiences that position **Engineering Mathematics** as a way to inform their engineering practice.

As a goal of P-12 Engineering Education, by the end of secondary school, engineering literate students should be able to recognize and, when appropriate, apply **Engineering Technical Applications** concepts to inform their engineering practice. **Engineering Technical Applications** is an interdisciplinary knowledge base consisting of the practical applications of engineering principles to bring ideas to reality and to operate and carry-out technical analyses of the tangible engineering outputs. This knowledge, which includes auxiliary concepts such as *electrical power*, *communication technologies*, *electronics*, *computer architecture*, *chemical applications*, *structural analysis*, *transportation infrastructure*, *geotechnics*, and *environmental considerations*, relies heavily on, and is inseparable from, the application of mathematical and scientific knowledge. The **Engineering Technical Applications** knowledge base is essential as engineering tasks are typically open-ended and ill-defined whereas different solution approaches may draw on a student's knowledge gained from a variety of domains.


Engineering Sciences
Knowledge of the basic principles and laws of the natural world in which engineers draw upon to solve engineering problems.
Engineering Technical Applications
Knowledge of the practical applications of engineering principles to bring ideas to reality and to operate and carry-out technical analyses of the tangible engineering outputs.
Engineering Mathematics
Knowledge of mathematical techniques and methods in which engineers apply within industry and research settings to better solve problems and complete tasks in a predictive manner.