Framework for P-12 Engineering Learning

A Defined and Cohesive Educational Foundation for P-12 Engineering

Advancing Excellence in P-12 Engineering Education &
the American Society for Engineering Education

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Advancing Excellence in P-12 Engineering Education (AE3)

In 2018 the AE3 research collaborative was founded as a nonprofit corporation, exempt under IRS Code Section 501(c)(3), that would conduct educational research, develop materials, and organize seminars to advance engineering education in P-12 schools. Today, AE3 consists of researchers, teachers, industry representatives, K-12 school-district partners, and policy makers with a shared vision to ensure that every child is given the opportunity to think, learn, and act like an engineer.

The AE3 research collaborative is an ongoing venture that promotes collaboration across the engineering and education community: first, to pursue a vision and direction for P-12 engineering learning, and second, to develop a coherent and dynamic content framework for scaffolding the teaching and learning of engineering in P-12 schools.

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AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Committee on a Framework for P-12 Engineering Learning

Greg J. Strimel (AE[3])
Committee Chair, Assistant Professor
Purdue University

Tanner Huffman (AE[3])
Framework Editor, Assistant Professor
The College of New Jersey

Michael Grubbs (AE[3])
Coordinator of Career & Technical Education
Baltimore County Public Schools

Jamie Gurganus (AE[3])
Associate Director of Engineering Education Initiatives
University of Maryland Baltimore County

Amy Sabarre
Director of STEM Education
Harrisonburg City Public Schools

Scott Bartholomew
Assistant Professor
Brigham Young University

American Society for Engineering Education

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Collaborators

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Ruth Akers
Baltimore County Public Schools

Ali Anderson
West Virginia University

Taryn Melkus Bayles
University of Pittsburgh

Gary Bertoline
Purdue University

P. J. Boardman
MathWorks

Lisa Bosman
Purdue University

Timothy Bosman
Gresham School District

Laura Bottomley
North Carolina State University

Robin Bowden
Baltimore County Public Schools

Keith J. Bowman
University of Maryland Baltimore County

Jennifer Buelin
ASHLIN Management Group

Shamara P. Collins
U.S. Department of Energy

Donovan Colquitt
Purdue University

Christopher Coombs
The College of New Jersey

Nicole Anne Culella
Mineola Union Free School District

Christine M. Cunningham
Pennsylvania State University

Martha Cyr
Worcester Polytechnic Institute

Michael A. de Miranda
Texas A&M University

Anita Deck
Concord University

Rachael Domer
Fairfax County Public Schools

W. Ethan Eagle
University of Maryland

Joshua A. Enszer
University of Delaware

Cheryl Farmer
University of Texas at Austin

Manuel Figueroa
The College of New Jersey

Dan Frey
Massachusetts Institute of Technology

Curtis Funkhouser
Berks Career & Technology Center

Wade H. Goodridge
Utah State University

Scott Greenhalgh
Utah State University

Matthew Halfacre
Princeton Public Schools

Douglas Handy
Baltimore County Public Schools

Robin A. M. Hensel
West Virginia University

Melinda M. Higgins
CNI Global Solutions LLC/U.S. Department of Energy

Avneet Hira
Massachusetts Institute of Technology

Teresa J. Irish
University of Maryland Baltimore County

Andrew Jackson
University of Georgia

Virginia R. Jones
Patrick Henry Community College

Taylor Kidd
Community College of Baltimore County

Eunhye Kim
Purdue University

Stacy Klein-Gardner
Vanderbilt University

Dale Krantz
Stephen Decatur High School

George Krause
Northrop Grumman Corporation

Liesl Krause
Purdue University

Mark Lastova
Linganore High School

Holly B. Lavender
Lancaster High School, Ohio

Jackelyn Lopez Roshwalb
University of Maryland

Pamela S. Lottero-Perdue
Towson University

Camsie McAdams
Discovery Education

Nathan Mentzer
Purdue University

Caitlyn Mesnard
Intralox

Megan Morin
North Carolina State University/University of North Carolina-Chapel Hill

Christine Newman
Johns Hopkins University

Scott Nichols
Maryland State Department of Education

Steve O'Brien
The College of New Jersey

Robbie Oehrli
Catonsville High School

Matthew Ohland
Purdue University

Joanna Papadopoulos
International Technology & Engineering Educators Association

Carolyn Parker
American University

Elizabeth Parry
Elizabeth Parry Consulting

Erin E. Peters-Burton
George Mason University

Edward M. Reeve
Utah State University

Mary Rinehart
1st Maker Space, LLC

David Sanders
SDI Innovations/STEM Education Works

Vanessa Santana
Purdue University

Sydney Serban
Purdue University

Susheela Shanta
Governor's STEM Academy at the Burton Center for Arts & Technology/Roanoke College

Nancy Shapiro
University System of Maryland

Raymond Sharp
Northrop Grumman Corporation

Bryan Silver
Albert Einstein Fellow/Kalani High School

Anne Spence
Baylor University

Tashia Tillett
Montgomery County Public Schools

Rebecca Turner
The College of New Jersey

Claire VerHulst
Johns Hopkins University

Angela Waldrop
Eastern Technical High School

David Walley
Reservoir High School

Bevlee Artis Watford
Virginia Tech

Bruce Wellman
Olathe Engineering Academy

Emily Yoshikawa
Weber Innovation High School

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Review

This framework was reviewed in its draft form by individuals active in the P-12 engineering education community. Reviewers were selected based on their expertise in the areas of a P-12 engineering teaching, research, professional development, and policy. The review of the *Framework for P-12 Engineering Learning* was overseen by Greg Pearson, National Academy of Engineering scholar emeritus. Neither he nor the reviewers were asked to endorse the content or recommendations of this manuscript, nor did they see the final draft before its release. During the review process, reviewer identities were known only to Mr. Pearson. While all reviewer comments were carefully considered by the authors, responsibility for the final content rests entirely with the Advancing Excellence in P-12 Engineering Education Research Collaborative and the American Society for Engineering Education.

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Maurice Frazier
Technology Teacher
Oscar Smith High School

Pamela Loterro-Perdue
Professor, Science & Engineering Education
Towson University

Doug Paulson
Director, Academic Standards and Instructional Effectiveness
Minnesota Department of Education

Senay Purzer
Associate Professor, School of Engineering Education
Purdue University.

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Preface

Motivation for the Framework for P-12 Engineering Learning

Many of us within the P-12 engineering education community recognize that there is something special about engineering learning. When given the opportunity to engineer, students of a variety of ages and backgrounds are motivated to learn and eager to engage in solving difficult problems. They work together. They communicate. They are critical and creative and resourceful. We've seen it with our own eyes, experienced it as teachers and professional development coordinators, and advocated for it at parent/teacher nights, school board meetings, and legislative briefings. Yet there has been little to no interest from the educational community in adopting engineering as central to the educational experience of every child. Engineering continues to be largely disguised as a vehicle for science education, or as career education for the few. This framework is for those of us who value engineering for the sake of engineering and the opportunities it opens for all students.

Vision and Implementation

The Advancing Excellence in P-12 Engineering Education (AE^3) research collaborative and the American Society for Engineering Education (ASEE) launched this effort to enhance the quality of P-12 engineering/engineering technology education across all school levels. The effort has been carried out through the publication of this report, the *Framework for P-12 Engineering Learning,* which provides a vision and structure for P-12 engineering, as well as associated grade-band specific implementation guides for elementary, middle, and high schools. These implementation guides identify specific concepts, learning goals, and performance expectations within the overarching framework presented in this report.

Goals of the Framework for P-12 Engineering Learning

This framework aims to provide guidance by identifying common P-12 engineering learning goals that all students should reach to become engineering literate. Ultimately, it is our hope that the framework will add structure and coherence to the P-12 engineering community in the following ways:

- Serve as a foundational document for the development of any and all engineering programs in P-12 schools.
- Inform state and national standards-setting efforts.
- Provide the educational research community with a common "starting point" to better investigate and understand P-12 engineering learning.

The *Framework for P-12 Engineering Learning* is intended to be a dynamic and useful document that will be continually informed by the research community. Our goal: Make engineering part of every child's educational experience by providing a toolkit to empower educators, engage students, evaluate curricula, improve instruction and teacher professional development, and guide policy decisions. We invite readers to join us in promoting the message that 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, when appropriate, Engineering Knowledge to confront and solve the problems that they encounter. Help us realize this shared vision for educating tomorrow's innovators.

Best regards,

Tanner Huffman, Ph.D.
Executive Director
Advancing Excellence in P-12 Engineering Education Research Collaborative

Foreword

I am pleased that you have decided to read this document. This framework is particularly meaningful to me as it provides an answer to a vexing question with which I have long wrestled.

For more than two decades, I have used the knowledge that came with getting three degrees in mechanical engineering to assist people in understanding what a good engineering learning experience can look like in P-12 classrooms. This was not done in isolation—as the inaugural director of Tufts University's Center for Engineering Education and Outreach in 1995, I started working with P-12 educators. In the process I learned as much, if not more, from them about effective teaching methods than they learned from me about engineering concepts and processes that they could implement in their classrooms. At the state level, I was part of the team that reviewed and suggested updates to the Massachusetts Science and Technology Framework for the 2000 version, when the first engineering standards were included, and the 2016 version, as the Next Generation Science Standards were being adopted by many states around the nation. On the national front, I was an integral member of the team that created the Pre-College Engineering Education Division within the American Society of Engineering Education in order to create a space and community that focused on P-12 engineering education. This community provided opportunities to have discussions with fellow university-level engineering colleagues about effective P-12 engineering education.

In all my conversations with these assorted groups, we struggled with defining exactly what is it that makes engineering unique as a field and how to translate that into illuminating P-12 student experiences. Yes, we use an engineering design process, but there is more to the discipline than that. Yes, we study and learn specialized areas of sciences, but many of those concepts occur as postsecondary learning. Yes, we are creators of new technologies and processes, but innovation occurs in many fields, and it is important to know what aspects of the creation process are relevant for P-12.

Successfully resolving these challenges has been goal of the Advancing Excellence in P-12 Engineering Education team, the authors of this framework. Each of the authors has a strong history of assisting with the implementation of engineering in P-12 classrooms. Each brings unique perspectives and experiences that when coalesced, debated, and tested have resulted in a powerful outcome. This team includes two school-level district administrators and four higher education faculty members. Their collective experience includes decades of K-12 STEM (science, technology, engineering, and mathematics) education teaching, hundreds of teacher professional development workshops, broad research expertise in engineering education, and advanced degrees in STEM education and mechanical engineering.

Every one of the authors has gone beyond talking and thinking about what defines a strong engineering learning experience for P-12 students to actively working on creating and/or providing those experiences. When they came together to start the work on Advancing Excellence in P-12 Engineering Education, their goal was to create a resource to guide the creation of authentic engineering learning experiences. In their words, they sought to *"establish a consistent epistemic basis for engineering learning and define engineering literacy for all students."*

They knew the effort would require input from a wider audience. To achieve this, schoolteachers, administrators, and representatives from industry and higher education were gathered for three annual symposia to provide contributions and feedback on their work in progress.

The resulting framework has captured all the aspects that I, and others, had struggled to piece together, and has linked them in a comprehensive, thoughtful, and helpful manner. It defines what is needed to be an engineering-literate student and the components associated with achieving engineering literacy.

An engineering-literate P-12 student has been engaged in systematic engineering learning throughout their schooling. Engineering learning can be thought of as having three primary components: Engineering Habits of Mind, Engineering Practices, and Engineering Knowledge. The framework lays out the elements for each of these three components and briefly discusses how elements can scale over the years of student learning. The framework emphasizes the importance of ensuring that engineering learning is equitable and socially relevant, in order to include all students.

How can you benefit from the *Framework for P-12 Engineering Learning?*

If you are part of a school system that is seeking to include, expand, or evaluate the rigor and comprehensiveness of engineering experiences for your students, this framework will be critical in your work.

If you are part of a state department of education, this framework should be used as you develop or revise your academic standards.

If you are a researcher with a focus on P-12 engineering learning, this framework outlines some of the potential starting points as well as aspects from a common starting point.

It is my hope that you use this framework in a manner that supports the work you are doing at the individual, school, district, or state level to advance P-12 engineering education from the research-informed, well-thought-out, and common understanding that this framework provides.

Here's to helping ALL of our P-12 students become engineering literate!

Martha Cyr, Ph.D.
Senior STEM Education Center Fellow,
Worcester Polytechnic Institute
ASEE Fellow
Chair, Standards Committee of the
ASEE Commission on P-12 Education
American Society for Engineering Education

Executive 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 that 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 that ensures 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 and dynamic guide for defining engineering learning for students and for establishing the building blocks that set the foundation for a coherent approach for states, school systems, and other organizations to develop engineering learning progressions, standards, curricula, instruction, assessment, and professional development that 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, to cultivate their skills by actively engaging in engineering practices, and to inform their practices through the appropriate application of engineering concepts which 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 destinations—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 are pursuing postsecondary 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 to 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 regarding engineering learning:

> **Engineering Literacy** is the confluence of content knowledge, habits, and practices merged with the ability to communicate, 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 and focuses on the *Engineering Habits of Mind* (e.g., Optimism, Persistence, Creativity) that students should develop over time through repetition and conditioning, the *Engineering Practices* (Engineering Design, Materials Processing, Quantitative Analysis, and Professionalism) in which students should become competent, and the *Engineering Knowledge* (Engineering Sciences, Engineering Mathematics, and Technical Applications) that students should be able to recognize and access to inform their Engineering Practice. The goal of *Engineering Learning* is to foster *Engineering-Literate Students.* (See Table E-1 for details of each dimension.)
>
> 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—which are scientific, mathematical, and technical in nature.
>
> The **Goal of Engineering Literacy for All** is to ensure that every student, regardless of 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 as well as 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 that 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 students' understanding of engineering-related career pathways; and (4) set a solid foundation for those who may matriculate to a postsecondary program for an engineering-related career.

Table E-1. P-12 Engineering Content Taxonomy

ENGINEERING HABITS OF MIND	**OPTIMISM**	Engineering-literate individuals, 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. (National Academy of Engineering [NAE], 2019)
	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. (NAE, 2019)
	COLLABORATION	Engineering successes are built through collaboration and communication. Teamwork is essential. Engineering-literate individuals are willing to work with others. They are skilled at listening to stakeholders, thinking independently, and then sharing ideas. (NAE, 2019)
	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 engineering-literate individuals excel. Finding new ways to apply knowledge and experience is essential in engineering design and is a key ingredient of innovation. (NAE, 2019)
	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 i the moral issues that may arise from the work. (NAE, 2019).
	SYSTEMS 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, engineering-literate individuals need to be able to recognize and consider how all those different systems are connected. (NAE, 2019)

ENGINEERING PRACTICE	**ENGINEERING DESIGN**	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)
	MATERIAL PROCESSING	Material Processing is the practice that engineering-literate individuals use to convert materials into products, often referred to as making. 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.
	QUANTITATIVE ANALYSIS	Quantitative Analysis is the practice that engineering-literate individuals use to support, accelerate, and optimize the resolution of 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.
	PROFESSIONALISM	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 design decisions that protect the public's well-being, improve society, and mitigate negative impacts on the environment.

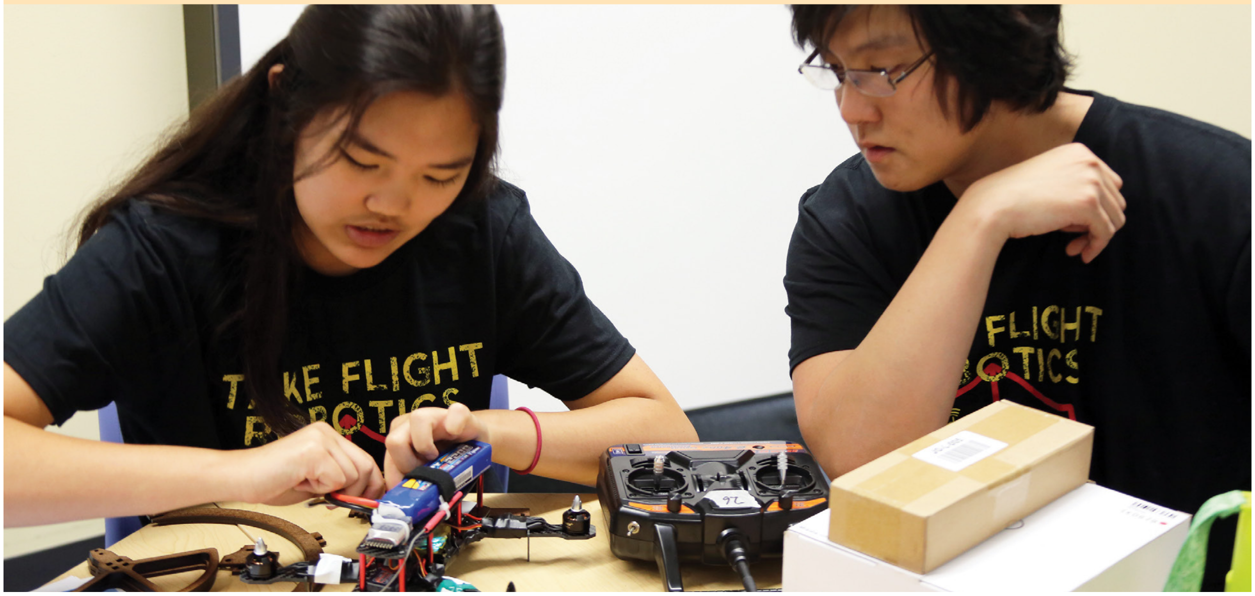
ENGINEERING KNOWLEDGE	**ENGINEERING SCIENCES**	Engineering Science is a knowledge base consisting of the basic principles and laws of the natural world that engineering professionals draw upon to complete engineering tasks.
	ENGINEERING MATHEMATICS	Engineering Mathematics is a knowledge base consisting of practical mathematical techniques and methods that engineering professionals apply within industry and research settings to better solve problems and complete engineering tasks in a predictive manner.
	ENGINEERING TECHNICAL APPLICATIONS	Engineering Technical Applications is an interdisciplinary knowledge base consisting of the practical engineering principles necessary to bring ideas to reality and to operate and carry out technical analyses of tangible engineering outputs.

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:

Keep Equity at the Forefront – Engineering plays a vital role in America's economic well-being and opens pathways to fulfilling careers in areas from agriculture to medicine to sustainable energy. But many students, particularly girls and underrepresented minority youths, remain unaware of or underserved with regard to these opportunities. Achieving engineering literacy for all thus 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 shaped by deliberate efforts to ensure equitable approaches to engineering. Similarly, any related educational initiatives resulting from the framework must make sure that there are appropriate supports provided, based on individual students' needs, so that all can achieve the same 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 that is authentic to engineering. If not, we may expose children to something *called* engineering, which they dislike and therefore never explore the actual field. Concurrently, we may mislead or underprepare them by providing activities that they do enjoy but which have little relation to authentic engineering practice.

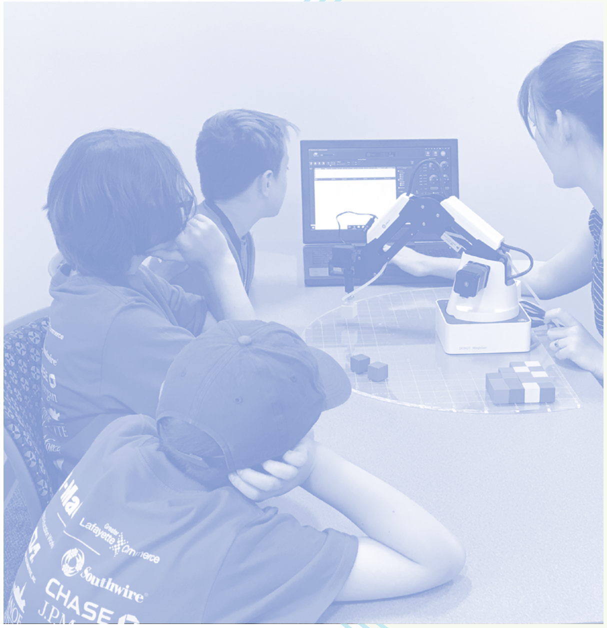
Focus on Depth over Breadth - Instead of providing students with broad learning objectives such as "apply the engineering design process to solve a problem," engineering concepts should be detailed to a level of specificity necessary to scaffold learning in a way that enables a student to perform engineering 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 by 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 require 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 students making products and systems, both physical and digital, 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, and Medicine, 2018). This type of learning can scaffold age-appropriate tool knowledge and techniques that are 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, and 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 could be aligned to student communities through socially relevant and culturally situated contexts. These applications can be one method of helping students learn engineering concepts and practices and hopefully make engineering seem more relevant. Therefore, any ways in which this framework is used for developing standards, learning progressions, and/or curricula should intentionally model learning experiences that are contextualized in ways that are socially relevant and culturally responsive to students.



Chapter I

A Vision & Rationale For P-12 Engineering Learning

While current initiatives in P-12 engineering learning are promising, a major void has been a broadly accepted vision and roadmap that promotes a shared understanding of the role of engineering within elementary and secondary schools and that helps address the inequities of authentic engineering experiences across schools. This document, titled the *Framework for P-12 Engineering Learning,* presents a cohesive and dynamic guide that establishes a consistent epistemic basis for engineering learning and that defines engineering literacy for all students. The framework has been developed, through years of stakeholder engagement, to foster a P-12 engineering learning community with a shared vision and direction that will enable all students to think, learn, and act like engineers, and ultimately become engineering literate. Accordingly, the goal of this framework is to provide the building blocks necessary to set the foundation for a coherent approach for states, school systems, and other organizations to develop engineering learning progressions, standards, curricula, instruction, assessment, and professional development that better democratize engineering learning across grades P-12. The aim of this approach is to enhance the authenticity, rigor, depth, and coherency of engineering concepts and practices that are addressed in P-12 classrooms and to do so in a manner that strives to achieve equity in engineering learning for all students.

Framework Rationale

The educational benefits of engaging children in engineering experiences continue to be promoted (Cunningham et al., 2020; Grubbs, Strimel, and Huffman, 2018). However, minimal attempts in the United States have been made by the education community to establish the deliberate and coherent study of engineering from a national perspective (Chandler, Fontenot, and Tate, 2011; Moore et al., 2014; National Academy of Engineering (NAE), 2017; National Academies of Sciences, Engineering, and Medicine (NASEM), 2020; Samuels and Seymour, 2015). Specifically, few efforts have been undertaken to identify developmentally appropriate content and practices for scaffolding the teaching of engineering (Strimel, Huffman, Grubbs, Kim, and Gurganus, 2020). Regardless, engineering continues be taught in P-12 schools, but without a defined and consistent goal specific to engineering as a discipline. Without such a framework and a well-defined vision, teachers may find the implementation of P-12 engineering learning challenging and face difficulty in teaching in-depth and authentic practices of engineering (Brophy, Klein, Portsmore, and Rogers, 2008; Daugherty and Custer, 2012; Farmer, Klein-Gardner, and Nadelson, 2014; Locke, 2009; NAE, 2017; NASEM, 2020; Reimers, Farmer, and Klein-Gardner, 2015). This can continue to contribute to the unevenness, inconsistency, inauthenticity, and inequity of engineering learning across the country (NAE and National Research Council (NRC), 2009; National Assessment of Educational Progress (NAEP), 2016; 2018; Samuels and Seymour, 2015).

These concerns highlight three major obligations for developing a national *Framework for P-12 Engineering Learning:*

1. Access to, and equity of, engineering learning experiences,
2. Consistency and coherency of the engineering learning initiatives that are implemented across the country, and
3. Authenticity and depth in the engineering habits, knowledge, and practices that are taught to the nation's youth.

Access & Equity

As engineering endeavors continue to provide solutions to the world's most daunting problems, the demand for high-quality engineers and other related STEM professionals continues to increase (Change the Equation, 2016; ManpowerGroup, 2015; Noonan, 2017). Also, an engineering-literate society is believed to be better positioned to assess, value, and, ultimately, support political positions that aim to advance our engineering and scientific capacity. As a result, achieving engineering literacy for all students should be a goal of our nation's education system and specifically the main purpose of any engineering learning initiative. However, many of the nation's youth lack the learning experiences that intentionally teach the concepts and practices necessary to become engineering literate during their typical school day. This is evidenced by the results of the National Assessment of Educational Progress in Technology and Engineering Literacy (2016; 2018), which continue to reveal that less than half of the nation's eighth graders tested are at, or above, the proficient level. Moreover, the results of this national assessment have exposed that low-income and underserved minority youth lag farther behind their white and Asian peers in engineering literacy, as they typically have the least exposure to engineering coursework during school. Unfortunately, it seems that a student's exposure to engineering learning is often left to chance, based on their ZIP Code (Change the Equation, 2016), family's income, and ethnicity, as engineering learning experiences are often not required for all students.

This great disservice to our nation's youth can be partly attributed to the deficit of a defined basis for engineering learning aimed toward achieving engineering literacy as a core component of a student's general education (Samuels and Seymour, 2015). This signifies a need for developing a coherent educational approach based on a consistent operational definition of the components of engineering learning and literacy. Increasing opportunities for all students to engage with engineering learning can be one step toward improving the much-needed diversity of the workforce and, eventually, help to advance the technological and innovative output of our nation. Therefore, a major objective in developing the *Framework for P-12 Engineering Learning* is to help all schools, not just those with abundant resources, offer engineering learning experiences as an opportunity for all students, rather than an amenity for the few. By defining the outcome of engineering literacy (i.e., how students should think and what they should know and be able to do by the end of secondary school), education stakeholders can then outline the content that teachers will need to be prepared to teach and develop the learning pathways toward a distinct academic goal.

Providing a coherent view of the performance expectations necessary for achieving engineering literacy can help to ensure that any curriculum or standards reflect all the key stages in engineering learning and that additional, out-of-school opportunities, which many students lack access to, are not necessary to achieve engineering literacy. In addition, Chapter 3 of the framework provides guidance to help educators develop and implement curriculum and instruction in a manner that connects engineering learning with students' cultures, communities, families, interests, and society as a whole, in an attempt to develop a sense of belonging within, and personal relevance to, engineering. Intentionally modeling contextualized learning experiences in ways that are socially relevant and culturally responsive to students can be one approach to reaching more students, showcasing how their backgrounds are important to the practice of engineering. This approach can also play a role in addressing misperceptions around engineering-related careers. Accordingly, this framework strives to add value toward promoting diversity in engineering by modeling equity and inclusion through the development and implementation of a comprehensive definition of engineering learning and performance expectations for the end of secondary school.

Consistency & Coherency

As engineering is still an emerging subject in P-12 schools (Reed, 2018), there is much to learn about how students interact with engineering curriculum and instruction. Specifically, few efforts have been undertaken to identify developmentally appropriate content and practices (i.e., standards/learning progressions) for scaffolding the teaching of engineering (NAE, 2017; NASEM, 2020). While national educational standards in science (NGSS Lead States, 2013) and technology (ITEA/ITEEA, 2000/2002/2007) have included engineering practices and content as a way to *facilitate* design-based teaching, engineering continues be taught within P-12 schools without a defined and consistent goal specific to engineering as a discipline.

To illustrate the concerns of consistency and coherency of engineering experiences, consider any one of the "common engineering-oriented instructional activities," such as assigning students to design and make a load-bearing structure. As an instructor, one must consider a multitude of standards as well as the prior knowledge of the students. As compared to a Mathematics, English Language Arts, or Science learning objective, one can moderately recognize where students' prior knowledge begins and ends based on the type of courses they may have completed. Conversely, within a high school engineering learning experience, some students may have been exposed to a middle school engineering course, or prior learning experience, while others have not. Instructionally, this can be a challenge, when compared with instruction in other disciplines. Mathematics, Science, and English Language Arts, even non-core areas such as Fine and Visual Arts, have deliberate pathways from preschool through high school, even deviating for students' developmental abilities (e.g., Talented and Gifted Education, Special Education, and English Language Learners). This instructional challenge is compounded when the teacher implementing the instructional activity may have little to no formal training related to teaching engineering. These teachers are then left with limited resources to draw upon when establishing the appropriately scaffolded engineering learning objectives necessary to foster a student's growth toward engineering literacy. Accordingly, a coherent and consistent approach throughout grades P-12 is key to realizing the vision for engineering learning embodied in this framework, which involves ensuring that all students, over multiple years of school, have the opportunity to orient their ways of thinking through developing engineering habits of mind, to cultivate skills by actively engaging in engineering practices, and to inform these practices through the appropriate application of the engineering concepts, which are scientific, mathematical, and technical in nature. Facilitation of this process can allow for a student to truly develop an integrated mindset for learning and problem solving that is often deemed necessary for their capability to thrive in the society of tomorrow. Consequently, this framework represents the first step in a process that should inform state-level decisions and provide a research-grounded basis for improving a cohesive approach to engineering teaching and learning across the country.

Authenticity and Depth

While implementation efforts such as the *Next Generation Science Standards* (NGSS) have led to science teachers throughout the country teaching engineering design as a "supplement to" and "a vehicle for" science learning, these standards and other educational initiatives may provide a too narrow view to adequately define and implement authentic engineering, specifically concerning content and competencies beyond design (Huffman, 2019). This was an initial concern within the engineering communities (e.g., Hosni and Buchanan, 2013; Fortenberry, 2018), as the lack of authenticity could 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 teach engineering authentically is intimately tied to the understanding of engineering as a discipline. Without a framework that is true to engineering as its own discipline, one must question whether typical "engineering-oriented" activities (build a tower, design a bridge, create a toy car, etc.) (a) accurately depict the practices of engineering, (b) leverage engineering knowledge to inform student practice, and (c) fortify engineering habits of mind; or if they just provide a "fun, hands-on reprieve" from typical learning environments. The potential lack of authenticity and absence of increasing rigor/sophistication of engineering learning over time from such instructional activities could lead to a misrepresentation of engineering and reduce opportunities for students to further their knowledge and capabilities. In addition, we may expose children to something called engineering, which they dislike and therefore never explore the actual field, and, concurrently, we may mislead or underprepare them by providing activities that they do enjoy but which have little relation to engineering practice.

To illustrate the challenges of authenticity and depth related to the implementation of engineering learning experiences, consider again a common "engineering-oriented" activity such as assigning students to design and make a load-bearing structure. Students often can be seen engaging with the task, enacting a trial-and-error approach to make a structure using the readily available materials, testing the structure to failure, and celebrating when their structure holds the most weight. While this may be exciting, the experience may lack the intentional learning of specific content and the further development of a student's engineering capabilities (Grubbs and Strimel, 2015). Moreover, these types of "engineering-oriented" activities can be seen implemented across the grade levels without increases in authenticity and sophistication. For example, it is not uncommon to find students building model bridges and destructively testing them as an "engineering activity" in elementary classrooms, middle school classrooms, high school classrooms, and even in postsecondary courses, often without the scaffolding of more in-depth knowledge and practice (Strimel, 2019; Strimel, Bartholomew, Kim, and Cantu, 2018; Strimel, Bartholomew, Kim, and Zhang, 2018). This can be a concern, as engineering teachers providing design activities may be falsely comforted by an expectation that their students are successfully identifying and learning the often difficult-to-understand, discipline-specific engineering concepts from these experiences in a manner that can be transferred to novel contexts (Antony, 1996; Berland and Busch, 2012; Goldstone and Sakamoto, 2003; Kaminski et al. 2009).

To better facilitate an appropriate engineering activity that is developmentally rigorous and authentic, defined engineering concepts and practices can enable the creation of learning experiences that scaffold the content that students are expected to discover and apply. Consider again the load-bearing structure activity, but now with defined engineering concepts such as those presented in Figure 1-1. These concepts can now orient the activity to be authentic to engineering as well as provide depth in the intentional content and practices to be learned.

Figure 1-1. Engineering content for an example of a load-bearing structure activity

ENGINEERING CONCEPTS	STRUCTURAL ANALYSIS	STATICS	PROJECT MANAGEMENT
SUB-CONCEPTS	• Physical Properties of Building Materials • Deflection • Deformations • Column & Beam Analysis • Implementation of Design Codes	• Resultants of force systems • Equivalent force systems • Equilibrium of rigid bodies • Frames & trusses • Centroid of area • Area moments of inertia	• Initiating & Planning • Scope, Time, & Cost Management • Risk, Quality, Teams, & Procurement • Product Life Cycle Management

In contrast, some current engineering-related standards may only provide students with broad learning outcomes, such as: *students can use the design process to create a structure.* However, with the engineering concepts articulated in this framework (see Chapter 2 and Appendix A), the instructor can provide a level of depth, specificity, and rigor that meets students where they enter the activity and guides them to mastery, challenging them based on their prior knowledge. For example, using the sample *Engineering Performance Matrix* depicted in Figure 1-2, an instructor and students can more effectively assess learning progress, enabling solutions to a proposed engineering task through a challenging process that results in increased learning of intentional content and applications of engineering habits and practices. Within the load-bearing structure activity mentioned earlier, some students may be discovering the role of building codes when designing a structure, while others are applying and implementing building codes into their solutions. Establishing learning experiences in this manner can help instructors meet students where they are, based on their lived experiences, and serve them according to their needs. With this type of knowledge the instructor can be better prepared to differentiate instruction for a wide range of students, through individual, whole-group, or small-group coaching. As such, this process can be more meaningful, as it is customized to where students are as learners and will better aid them in tackling issues they encounter in the future, as they metacognitively reflect on the individual process that they deployed to navigate a challenge and develop a solution. Accordingly, this framework can help advance the authenticity and depth of engineering learning, spur the expansion of projects to build from explicitly developing engineering habits at a young age to the teaching of in-depth concepts necessary to inform authentic engineering practices in secondary school, and reduce the redundancies in "engineering-like" activities that are implemented in classrooms and that oftentimes lack increases in sophistication across the grade levels.

Figure 1-2. Engineering Performance Matrix example

Auxiliary Concept: Structural Analysis

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Engineering Literacy Dimension: Engineering Knowledge
Domain: Engineering Technical Applications
Overview: Structural Analysis concerns the process of determining the effects of loads, or forces, on physical structures, as well as their individual components, and examining what factors influence the deflection and deformation of these structural elements. This includes determining how and why structural elements may fail, break or deform, and preventing such failures. This concept is important to Engineering Literacy as all structures are constantly under some type of strain or stress due to a variety of forces applied to them. As such, structural analyses enable one to make informed decisions about how structures should be designed by performing the proper calculations to determine whether or not various structural members will be able to support the forces applied to them.

Performance Goal for High School Learners
I can, when appropriate, draw upon the knowledge of Structural Analysis content and practices, such as (a) the physical properties of construction materials, (b) material deflection, (c) material deformation, (d) column and beam analysis, and (e) the implementation of design codes, to evaluate the structural elements of an structure design using the proper formulas and conventions necessary to calculate the effects of applied stresses or strains.

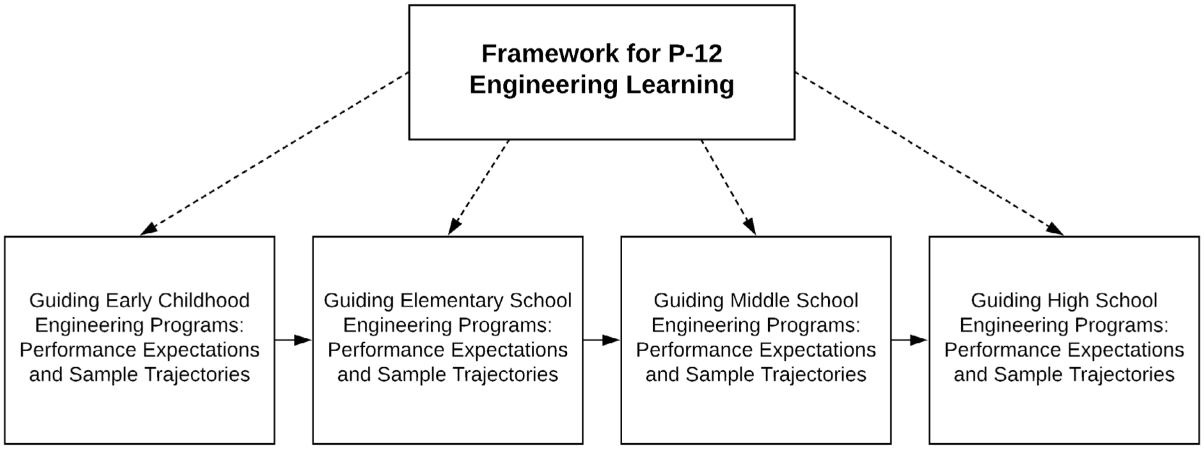
	Basic	Proficient	Advanced
PHYSICAL PROPERTIES OF BUILDING MATERIALS	I can list a variety of materials used for construction purposes and classify them in terms of their physical properties.	I can explain a variety of categories of building materials in terms of their strengths (e.g. concrete, moisture protection, thermal protection, fire suppression, etc.)	I can determine and justify which building materials are most appropriate for my design.
MATERIAL DEFLECTION	I can define structural deflection in beams, differentiating it from deformations.	I can explain the factors influencing structural deflection (e.g. load, length, Young's modulus, area etc.), using mathematical models.	I can analyze the possibilities of structural deflection of a given architecture design, using mathematical equations.
MATERIAL DEFORMATIONS	I can define structural deformations, differentiating it from deflection.	I can explain the factors influencing structural deformations (e.g. load, length, Young's modulus, area etc.), using mathematical models.	I can analyze the possibilities of structural deformations of a given architecture design, using mathematical equations.
COLUMN & BEAM ANALYSIS	I can describe the functions of columns and beams in architecture structures.	I can describe the basic factors influencing deflections or deformations of columns and beams (e.g. compressive, tensile, and shear stresses).	I can analyze the required forces of columns and beams for my design through column and beam analysis.

Framework Goal, Scope, and Audience

The *Framework for P-12 Engineering Learning* was developed as a unifying effort to enhance the authenticity, rigor, depth, and coherency of engineering concepts and practices that are addressed in P-12 classrooms, to connect with established engineering habits of mind, and to achieve equity in engineering learning for all students. This framework and any future companion documents seek to provide a comprehensive definition of engineering literacy for all students and the building blocks for setting the foundation for a coherent approach for states, school systems, and other organizations to develop student performance expectations, engineering learning progressions, standards, curricula, instruction, assessment, and professional development that help to better democratize engineering education across grades P-12. Put simply, the *Framework for P-12 Engineering Learning* is intended to inform (1) the revisions of current standards with respect to engineering AND (2) the development of new, stand-alone P-12 engineering standards if deemed appropriate. The *Framework for P-12 Engineering Learning* identifies the "Know," "Do," and "Act" for all students to become engineering literate. Follow-up publications, standards, and standards revisions would take the next step and identify how the "Know," "Do," and "Act" should be articulated across grade levels to achieve the goal of engineering literacy for all students.

While this framework does not specify grade-band learning expectations for the habits, practices, and knowledge of engineering, it does provide a destination or "endpoint" for each of these component ideas that details the understanding that students should have acquired by the end of secondary school. Associated grade-band specific implementation guides will leverage the content of this report to describe and propose appropriate engineering learning across the grades for all children to engage in rigorous and authentic learning experiences to think, act, and learn like an engineer (Figure 1-3). This approach is key to realizing the vision for engineering learning, embodied in the framework that all students, over multiple years of school, must have the opportunity to orient their ways of thinking through developing engineering habits of mind, cultivating skills by actively engaging in engineering practices, and informing these practices through the appropriate application of the engineering concepts, which are scientific, mathematical, and technical in nature.

Figure 1-3: Framework Scope and Future Goals



This framework aims to provide guidance by identifying common learning goals that all students should aim to reach in order to become engineering literate. It is our hope that the framework will add structure and coherence to the P-12 engineering community in the following ways:

- As a foundational document for the development of any and all engineering programs in P-12 schools.
- Inform state and national standards-setting efforts.
- Provide the educational research community with a common "starting point" to better investigate and understand P-12 engineering learning.

The *Framework for P-12 Engineering Learning* is intended to be a dynamic document that will be continually informed by the educational climate and by the research community. While this report remains a work in progress, we hope that it inspires you, the readers, to champion P-12 engineering education and promote the message that "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, when appropriate, *Engineering Knowledge* to confront and solve the problems that they encounter."

Framework Development and Guiding Principles

The framework development process involved iterative cycles of research, design, and experimentation in order to gather the data necessary to (1) articulate a vision for achieving engineering literacy for all, (2) establish a coherent theoretical and practical structure for the three dimensions of engineering learning, and (3) detail the understanding that students should acquire by the end of secondary school. (See Strimel, Huffman, Grubbs, Kim, and Gurganus, 2020.) This process specifically involved bringing together teachers, administrators, researchers, outreach coordinators, and educational organizations, as well as industry representatives, through a series of action-oriented symposia to (a) identify and refine an agreed upon taxonomy of concepts and sub-concepts for secondary engineering knowledge and practice, (b) formulate an instructional sequence for *Progressions of Learning in Engineering* at the secondary level, (c) create curricular examples for implementation using socially relevant/culturally situated learning activities, and (d) engage with a pilot site for testing and refining this work within secondary classrooms. As a result, the framework has been developed from over three years of research and development activity that has engaged over 300 P-12 engineering education stakeholders from 32 states and involved three multiday symposia that served as focus groups to provide concrete examples of best practices in P-12 engineering education from around the country.

Throughout this development process the following principles were established to guide the creation of this framework as well as the implementation of any resulting engineering teaching and learning initiatives:

1. Keep Equity at the Forefront
2. Strive for Authenticity to Engineering
3. Focus on Depth over Breadth
4. Build Upon Children's Natural Problem-Solving Abilities
5. Leverage Making as a Form of Active Learning
6. Connect with Student Interests, Culture, and Experiences

Keep Equity at the Forefront

Achieving engineering literacy for all requires that equity be at the forefront of any engineering learning initiative (Marshall and Berland, 2012; Strimel et al., 2020). 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. "The influences of environment and culture, from the molecular level to that of the broadest social and historical trends, affect what takes place in every classroom and every student." (NASEM, 2018, p. 137). Consequently, it is vital that educational strategies, such as culturally relevant pedagogy, are not just considered an extra component of curricula (Clausen and Greenhalgh, 2017). Instead, they must be integrated into the processes of content development, knowledge construction, unconscious bias elimination, pedagogical practice, and school culture (Banks, 2007). Mindful approaches must also be taken to establish coherence and articulation between engineering concepts necessary to reflect all of the key aspects of engineering literacy and to help ensure that additional, out-of-school opportunities, which many students may not have access to, are not needed to fill gaps in knowledge (K-12 Computer Science Framework, 2016). Not doing so may leave many students without the opportunity to achieve the goal of engineering literacy. 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 the same level 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 (Collins, Brown, and Newman, 1989; Daugherty and Custer, 2012; Reimers, Farmer, and Klein-Gardner, 2015). 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 children to something *called* engineering, which they dislike and therefore never explore the actual field, and, concurrently, we may mislead or underprepare them by providing activities that they do enjoy but which have little relation to authentic engineering practice. As discussed by the executive director of the American Society for Engineering Education, Norman Fortenberry (2018), knowledge of how to teach engineering authentically is intimately tied to the understanding of engineering as a discipline.

Focus on Depth over Breadth

Initial learning is specific (Woodworth and Thorndike, 1901), highly contextualized (Lave, 1988) and required for transfer (see "How People Learn," National Research Council, 2000, p. 53). 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 students to perform engineering practices well, and with increased sophistication, along the path toward engineering literacy. Therefore, this framework provides a deep dive into each of the dimensions of engineering learning by articulating concepts and practices along with the related sub-concepts necessary for scaffolding learning experiences. 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 (Kendall, 2017).

Build Upon Children's Natural Problem-Solving Abilities

People are born as natural problem solvers. As such, 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 (Dewey, 1897), specifically through the experience of failure (Lottero-Perdue and Parry, 2017; Strimel, Bartholomew, Kim, and Zhang, 2018). 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 (Crismond and Adams, 2012; Grubbs and Strimel, 2015). 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, that require use of appropriate mathematical, technical, and science concepts in conjunction with technological tools for optimizing solutions (Merrill, Custer, Daugherty, Westrick, and Zeng, 2009). By leveraging the specificity of the concepts outlined in this framework (see Appendix A), engineering experiences can be scaffolded across grade levels to help students develop competence in engineering practices and achieve enhanced problem-solving capabilities. Starting in the early grades, students could be provided with structured design problems, which will inherently be inauthentic, that allow them to build upon playful and experimental approaches to designing and problem solving. The structured problems can provide experiences for students to achieve some success as they begin building their engineering confidence and habits. However, as students develop and their knowledge deepens, they should be provided with more realistic and less-defined problems, which may provide them with opportunities to learn from failure and apply more rigorous conceptual and procedural knowledge. As students continue to grow and develop more analytic thinking abilities, they could then move from trial-and-error problem solving approaches to more informed design that includes more calculated engineering practices—which also necessitates the developmentally appropriate applications of engineering knowledge that is scientific, mathematical, and technical in nature (Strimel, Bartholomew, Kim, and Zhang, 2018). As a result, students can begin to competently enact authentic engineering practices with increased sophistication over time.

Leverage Making as a Form of Active Learning

The activity of students making products and systems, both physical and digital, provides them with experiential learning that engages them in constructing their own knowledge and orients their learning within real contexts (NASEM, 2018). This type of learning can scaffold age-appropriate tool knowledge and techniques that are 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. For example, the engineering concepts articulated within this report can be leveraged for students to construct their knowledge of technologies or tools across grade levels and engage them in more realistic challenges that increasingly require their knowledge of more complex and complicated technologies that are obligatory for engineering practice. As a result, any engineering-related educational activities resulting from this framework should leverage making as an active form of learning engineering practices, knowledge, and habits.

Connect with Student Interests, Culture, & Experiences

Engineering learning must include, value, and support learners of all kinds (Marshall and Berland, 2012). This involves connecting with student interests, culture, and experiences in an effort to make engineering learning relevant to their lives. This effort can be vital for removing barriers for students 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 (K-12 Computer Science Framework, 2016). However, this guiding principle requires ongoing efforts to learn about students and their families, which include truly getting to know who students are, both inside and outside of the classroom, to gain insights into how best to engage them in engineering learning (Clausen and Greenhalgh, 2017; Ladson-Billings, 1995; Scriven, 2019). This can play a major role in addressing the misperceptions around engineering-related careers and can help guide the creation of educational experiences that reach all students in a more personalized way. Therefore, any ways in which this framework is used for developing standards, learning progressions, and/or curricula should intentionally model learning experiences that are contextualized in ways that are socially relevant and culturally responsive to students.

The Case for P-12 Engineering Learning

Our world is full of seemingly insurmountable challenges: making solar energy economical, providing continued access to clean water, developing better medicines, and securing cyberspace, to name a few. Historically, engineering practices have solved the world's most daunting problems. But paramount to resolving such challenges is the need to prepare the next generation of engineering-literate global citizens. While the demands of our world require creative, capable, and diverse problem solvers, young learners have limited opportunities to engage in engineering as both a deliberate and cross-curricular component of their typical school day. While people interact with the human-made world nearly every moment of every day, individuals have very little understanding of how this world works and how it was created. Children in our schools spend years learning about the natural world but a glaringly insufficient amount of time studying the human-made world through engineering learning. As Ioannis Miaoulis, president emeritus of the Boston Museum of Science, famously highlighted the blatant omission in 2010, noting that students in middle school can spend weeks learning how a volcano works, and no time understanding how a car works. How often will they find themselves in a volcano?" While it is quite possible that some students today may have limited experiences with a vehicle, the overarching message rings true. Evidence of engineering, like science, is all around us. But educational experiences dedicated to understanding how engineering has designed and created technologies are blatantly inadequate when compared to adjacent STEM areas.

Many school systems have turned to STEM education in general 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 preparing the populace for the 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 curricula 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 to the promise of an informed and participating citizenry.

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 postsecondary training and expertise. Engineering is naturally integrative, calling upon scientific knowledge, mathematical truths, and technological capabilities to develop and optimize 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 learning 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. An engineering-literate citizenry would have immediate impact on our society. Young adults would be better prepared to participate in our democratic government, make decisions about careers, and improve their everyday livelihood with an engineering mindset.

Vision for P-12 Engineering Learning

The vision for P-12 Engineering Learning is to achieve **Engineering Literacy for All.** This includes ensuring 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 defined as the confluence of content knowledge, habits, and practices merged with the ability to communicate, think, and perform in a way that is meaningful within the context of engineering and the human-made world (Wisconsin Department of Public Instruction, 2011; Lent, 2015; Strimel et al. 2020). It is relevant not only to all individuals but also to communities and society as a whole. It is an attribute concerned with the journey that inventors, innovators, makers, designers, and literate citizens take while improving and interacting with the systems, products, and services of our world. These interactions require that an engineering-literate person become familiar with associated scientific, mathematical, and technical knowledge, as well as engineering practices and habits of mind.

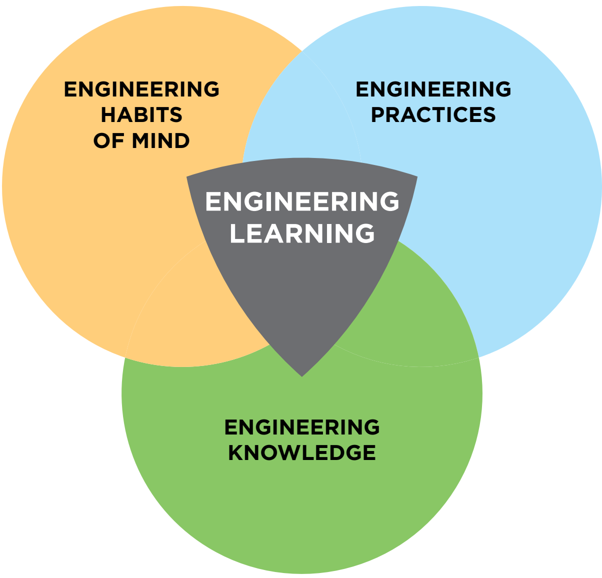
Engineering Literacy is achieved through **Engineering Learning,** which is three-dimensional (NAE and NRC, 2006; 2009; NAE, 2010; Sneider and Rosen, 2009) (see Figure 1-4) and focuses on:

1. *Engineering Habits of Mind* (e.g., Optimism, Persistence, Creativity) that students should develop over time through repetition and conditioning,

2. *Engineering Practices* (Engineering Design, Materials Processing, Quantitative Analysis, and Professionalism) in which students should become competent, and

3. *Engineering Knowledge* (Engineering Sciences, Engineering Mathematics, and Technical Applications) that students should be able to recognize and access, when appropriate, to inform their *Engineering Practice.*

Figure 1-4. Dimensions of Engineering Learning



Engineering literacy develops beginning in the early years of a child's education and extends through the completion of their secondary education goals. Therefore, by the end of secondary school all students must be provided the three-dimensional learning experiences that (1) cultivate habits of mind necessary to orient themselves to an engineering way of thinking, (2) engage them in authentic practices of engineering to resolve real challenges, and (3) require them to appreciate, acquire, and apply, when appropriate, scientific, mathematical, and technical concepts in relevant ways to better perform their engineering practice and confront and solve the problems that they encounter. The main components of the three dimensions of Engineering Learning are provided in Table 1-1.

Table 1-1 - Main Components of Three-Dimensional Engineering Learning

DIMENSION 1: ENGINEERING HABITS OF MIND	DIMENSION 2: ENGINEERING PRACTICES	DIMENSION 3: ENGINEERING KNOWLEDGE DOMAINS
Optimism	Engineering Design	Engineering Sciences
Persistence	Material Processing	Engineering Mathematics
Collaboration	Quantitative Analysis	Engineering Technical Applications
Creativity	Professionalism	
Conscientiousness		
Systems Thinking		

Engineering-Literate Individuals *are defined as* integrated learners who have 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—which are scientific, mathematical, and technical in nature.

Accordingly, an **Engineering Learning Initiative or Program** is a structured sequence of educational experiences that aims to achieve one or more of the following:

1. cultivate *Engineering Literacy* for all students, not just those interested in pursuing an engineering-related career,

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 postsecondary program for an engineering-related career (NASEM, 2020).

These aims, however, are not mutually exclusive. They can build upon one another. For example, engineering-literate students can better integrate concepts and practices across all school subjects and likely achieve better academic and technical success. Those who have integrative experiences and achieve success may then become more interested in engineering-related careers. Therefore, educators leading engineering learning initiatives should seek to advance their programs in creative and meaningful ways within their learning communities. For example, a comprehensive engineering program may seek to achieve these goals entirely within the formal education experiences. Conversely, a different program may seek to cultivate engineering literacy for all students with formal classroom instruction while also providing informal opportunities to assist in integration and career readiness.

Positioning of P-12 Engineering Learning

Engineering, as a school subject, is inherently integrative, as it calls upon scientific knowledge, mathematical truths, and technological capabilities to design solutions to societal, economic, and environmental problems. The role of engineering within P-12 schools has come in various shapes and sizes; from pervasive to "complementary to" typical instruction specifically within science classrooms. While engineering is intimately coupled to science, engineering is not just a topic of science. As such, it is necessary to describe the bifurcation of, but also, the connections between, science and engineering. The following excerpt from Sharp (1991) helps to clarify this point.

> Engineers generally think of themselves as problem solvers. Different from scientists, who examine the world around them to obtain an understanding of things as they are and have been, engineers are concerned with creating something new, something which is currently not in existence and which never has been. For example, Scientists, such as Geographers, and Engineers are both interested in the science of Hydrology which deals with climate, precipitation, floods and droughts. The Geographer measures rainfall and the resulting floods to understand, among other things, how river flows respond to rainfall, how much water runs off the land, how much is stored and how much is evaporated. The measurements are made to obtain a picture and understanding of existing natural phenomena and the inter-relationship among them to make conclusions and/or predictions. Engineers make identical measurements and make use of identical data but for quite different reasons. Frequently engineers are called upon to design and construct structures which must cope with the effect of moving water; e.g. drainage channels from parking lots, storm water sewers, culverts under roads, bridges across rivers, flood-control works, irrigation schemes and dams and reservoirs etc. (Sharp and Sawden, 1984). For each of these it is important to predict future values of rainfall or river flow and this is done using the hydrological records collected in the past years. These records then are only a means to an end for the engineer.
>
> In addition to formulating the picture of current and past events the engineer must use these records to make statistical predictions of what is likely to happen in the future. Only with this knowledge is it possible to construct, for example, a new dam with a reasonable assurance that it will cope with the natural phenomena to which it will be subjected throughout its lifetime. Each new construction, regardless of size, represents a problem which must be solved and it is for this reason that engineers tend to think of themselves as people who have been educated primarily to solve problems. (p. 147)

Science and engineering are related in a unique way, as they share many core ideas and complementary practices yet are distinctive in their aims and values. Engineering tends to be about shaping the world, and science tends to be about discovering secrets of an already established natural world. As described by Peters-Burton (2014):

> These differences in focus can be considered harmonious, two sides of the same coin. One side (engineering) is the study of humans influencing the world, and the other (science) is about humans understanding the mechanisms in nature. The two sides inform each other, particularly when dealing with complexities of modern-day issues, such as climate change. Perhaps the reason these subjects dovetail so well is that when coupled, they have the capacity to describe the intricacies of, and interactions between, natural phenomena and the human made world. (p. 100)

Peters-Burton also notes that the more people discover about the world around them, the better they can refine ideas and tools to shape the surrounding environment. Similarly, the greater the accuracy with which they can anticipate the associated benefits, costs, and risks involved, the more harmoniously communities can coexist.

Put plainly, no P-12 engineering framework is complete without compelling associations to science, and no P-12 science standards are complete without compelling associations with engineering. This is important, as engineering rarely has a place in the general curricula of schools and is often implemented as a component of more broadly accepted science, technology, and mathematics courses (Marshall and Berland, 2012). As such, many of the teachers who will ultimately teach engineering will likely have a background in these other subjects rather than engineering. However, this framework, and companion implementation guides, will aim to fill the gap in knowledge and resources for the deliberate and coherent study of engineering. That being said, **this document is intentionally situated as support for engineering learning rather than engineering education, as there will continue to be different avenues for the implementation of engineering across school districts.** As recommended by the NAE (2010), there should remain opportunities for implementation within science education programs as well as Career and Technical Education. It is important to be clear that the *Framework for P-12 Engineering Learning* is aligned with and complementary to *A Framework for K–12 Science Education.* As discussed earlier, it is expected that any framework for science education has compelling associations with engineering. *A Framework for K-12 Science Education* (2012) does just that. Science and engineering practices presented in *A Framework for K-12 Science Education* aim to, among other things, "raise engineering design to the same level as scientific inquiry in science classroom instruction" (p.437), through the description of a "key set of engineering practices that engineers use as they design and build models and systems" (p.1, National Science Teachers Association, 2013). While *A Framework for K-12 Science Education* does a commendable job describing *engineering design practice* and related core ideas, engineering learning is much more. Engineering practice extends beyond design, as engineering-literate individuals are also concerned with materials processing or making, quantitative analysis, and professionalism (Strimel et al., 2020). This is specifically noted in the *Next Generation Science Standards* (NGSS) which states that the engineering design-related science standards "do not represent the full scope of such courses or an engineering pathway." Furthermore, engineering learning draws upon associated scientific, mathematical, and technical knowledge, especially as grade-levels increase and a more sophisticated understanding of engineering is desired. The *Framework for P-12 Engineering Learning* specifies these associated concepts to propose a more comprehensive engineering learning experience. Of course, depending on the grade level, the necessity of connecting to science content beyond that described in *A Framework for K-12 Science Education* and *NGSS* varies. For example, at the elementary level, it is expected that the engineering learning would draw nearly exclusively from *NGSS,* as much of the perquisite knowledge for advance understandings in both science and engineering are similar, and the elementary teachers will likely be responsible for both subjects. Conversely, there are advance applications of engineering that high school classrooms may need to cover that are beyond the scope of *NGSS* (e.g., Circuit Theory). As described in this framework, elementary engineering learning should integrate concepts from the *NGSS,* middle school engineering learning should enhance *NGSS* concepts, and high school engineering learning should extend beyond *NGSS.* Additionally, this framework should be similarly positioned with standards documents from other adjacent fields of study as well, such as Computer Science Education (see CSTA K-12 Computer Science Standards), Technology Education (see Standards for Technological Literacy) and Math Education (see Common Core State Standards for Mathematics).

Therefore, this framework positions engineering learning as the mechanism to ensure all students have the experiences necessary to (1) orient their ways of thinking by developing *Engineering Habits of Mind* and (2) be able to competently enact the *Engineering Practices* defined in this framework. However, the *Engineering Knowledge* dimension is only defined as the scientific, mathematical, and technical areas that students should appreciate and be able to draw upon, when appropriate, to better perform the practices of engineering. Students are not expected to fully understand the entirety of these domains of engineering knowledge in depth by the end of secondary school. But to be engineering-literate individuals, students should 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 Practices,* to confront and solve the problems that they encounter. Nevertheless, the full breadth of the *Engineering Knowledge* presented in this framework as auxiliary concepts can be leveraged to move interested students beyond general engineering literacy and shift instruction toward the preparation of future engineering professionals through *Career and Technical Education* pathways and connections with postsecondary engineering and technology programs. A fully articulated P-12 engineering program may scaffold learning expectations for the three dimensions of engineering learning depending on grade band, resources, teacher experience and expertise, student needs and backgrounds, and community influences. A typical scaffolding of the dimensions across grade levels to achieve engineering literacy may see the development of habits and practices earlier than engineering knowledge concepts, as the habits and practices are "core" to engineering literacy (Figure 1-5).

Figure 1-5. A proposed scaffolding of the dimensions of engineering learning across the grade levels

	EARLY CHILDHOOD PREK-2	ELEMENTARY 3-5	MIDDLE 6-8	HIGH 9-12
Habits				
Practices				
Knowledge				

- Beginning
- Developed
- Proficient
- Mastery

Early Childhood (Grades PreK-2) – Focus is on developing engineering habits of mind and on introducing engineering practices and engineering knowledge concepts.

Elementary (Grades 3-5) – Focus is on developing engineering habits of mind and engineering practices and on introducing engineering knowledge concepts.

Middle (Grades 6-8) – Focus is on building proficiency in engineering habits of mind and engineering practices and on developing engineering knowledge concepts.

High (Grades 9-12) – Focus is on building mastery of engineering habits of mind and engineering practices and on building proficiency in engineering knowledge concepts.

While the main goal of this framework is to achieve general engineering literacy for all students, regardless of career interests, an equitable approach to three-dimensional *Engineering Learning*—that aims to remove barriers to engineering engagement—may lead to more students interested in potential engineering-related career pathways. Therefore, it is important for *Engineering Learning Initiatives or Programs* to also enhance students' understanding of engineering-related career pathways and to set a solid foundation for those who may be, or become, interested in matriculating to a training or postsecondary program for an engineering-related career. Accordingly, the content and principles provided in this framework can be used to support students in moving beyond general engineering literacy and beginning a journey toward an engineering-related career. This includes career and technical education pathways as well as connections to first-year engineering programs. However, it is important to note that whether a student decides to major in engineering or not, the elements of *Engineering Learning* set forth in this framework align with developing the traits and characteristics of all individuals (e.g., collaborative problem solvers, integrators of knowledge and practice, effective communicators, ethical thinkers, etc.) that are often sought by both employers and postsecondary institutions across sectors and degree programs.

This document is intentionally situated as support for engineering learning rather than engineering education, as there will continue to be different avenues for the implementation of engineering across school districts.

GUIDING PRINCIPLES FOR ENGINEERING LEARNING

Engineering is a social responsibility. Therefore, we must ensure all students have the opportunity to develop engineering literacy. Accordingly, we have established six Guiding Principles for Engineering Programs. They are:

1. keeping equity at the forefront,
2. striving for authenticity to engineering,
3. focusing on depth over breadth,
4. building upon children's natural problem-solving abilities,
5. leveraging making as a form of active learning, and
6. connecting with student interests, culture, and experiences.

Summary

Although millions of students participate in engineering learning activities (Marshall and Berland, 2012), a major problem has been the lack of broadly accepted P-12 engineering standards/learning progressions and a shared understanding of the role of engineering within primary and secondary schools. However, this framework has been developed to provide a cohesive and dynamic guide for P–12 engineering learning by identifying and defining the three dimensions of engineering learning (Dimension 1: Engineering Habits of Mind, Dimension 2: Engineering Practices and Dimension 3: Engineering Knowledge). Specifically, the framework describes the end goal for achieving engineering literacy for all students and details the concepts necessary to authentically act, learn, and think like an engineer. The community that has developed and supported this project believes that such consistency can help ensure a more equitable approach to the delivery of engineering at the P-12 level, as teacher preparation programs, curricula, assessment, professional development opportunities, and alternative licensure programs, can be built around this framework for the most comprehensive support model possible. As such, this framework can ultimately serve as an initial step to inform, inspire, and drive the implementation work required to make the vision of the framework a reality and help set the foundation for the development of standards/learning progressions to support coherent educational pathways in engineering.

Chapter 1 outlined a shared understanding of the role of engineering within schools, including a vision and rationale for the school subject as well as a cohesive lens for defining the end goal of engineering literacy for all. The next chapter will provide an operational definition of the components of the three dimensions of engineering learning and outline the structure and content for the study of engineering. More specifically, Chapter 2 will specify the destination or "endpoints" for each component idea of engineering literacy and detail the understanding that students should acquire by the end of secondary school.

Chapter II

Content for the Study of Engineering

It is important to note that this framework document aims to provide (1) a comprehensive definition of engineering literacy for all students and (2) the building blocks for setting the foundation for a coherent approach for states, school systems, and other organizations to develop engineering learning progressions, standards, curricula, instruction, assessment, and professional development that helps to better democratize engineering learning across grades P-12. While this framework *does not* specify grade-band learning expectations for the habits, practices, and knowledge of engineering, it does provide endpoints for each component idea that describes the understanding that students should have acquired by the end of secondary school. However, associated grade-band implementation guides should leverage the content of this report to set and articulate engineering learning across the grades. This approach can help schools provide the opportunity for children to engage in rigorous and authentic learning experiences that enable them to think, act, and learn like engineers.

The comprehensive set of student expectations detailed in this chapter are positioned to inform the development of state and national standards and/or learning progressions that can then guide the creation and implementation of engineering-related curricula, instruction, assessment, and educator preparation and professional development. In doing so, a coherent and consistent approach throughout grades P-12 can be promoted, which will be vital for realizing the vision for engineering learning embodied in this framework (NRC, 2012). This vision focuses on achieving engineering literacy for all students over multiple years of schooling and should enable them to (1) orient their ways of thinking through developing engineering habits of mind, (2) cultivate their skills by actively engaging in authentic engineering practices, and (3) inform their practice through the appropriate application of engineering concepts, which are scientific, mathematical, and technical in nature. Facilitation of this process allows for a truly integrated mindset for learning and problem solving. As a result, this research-grounded framework is a seminal step in informing state- and local-level decisions for improving the coherency and equity of engineering teaching and learning across the country. The following sections of this chapter will provide an operational definition of the components of the three dimensions of engineering learning and outline the structure and content for the study of engineering. In addition, this chapter will specify the "endpoints" for each component idea of engineering literacy, which will detail the understanding that students should acquire by the end of secondary school. **The complete descriptions of the Engineering Literacy Expectations for High School Learners are provided in Appendix A.**

Defining the Dimensions of Engineering Learning

Defining the three dimensions of *Engineering Learning* will aid in determining how a student's educational progress should be supported and measured. While these dimensions are presented independently throughout this chapter, in order to facilitate student learning, the dimensions must be woven together in standards, curricula, instruction, and assessments (see Figure 2-1). Table 2-1 provides a high-level P-12 content taxonomy related to the three dimensions, which was informed by a multi-year study conducted by Strimel et al. (2020). First, the taxonomy highlights the six *Engineering Habits of Mind* (Optimism, Persistence, Collaboration, Creativity, Conscientiousness, and Systems Thinking) and describes the type of thinking that should be encouraged and rewarded throughout engineering learning experiences in order to orient a student's routine thought processes. Next, the taxonomy lists the four comprehensive *Engineering Practices* (Engineering Design, Material Processing, Quantitative Analysis, and Professionalism). Lastly, the taxonomy divides *Engineering Knowledge* into three domains (Engineering Sciences, Engineering Mathematics, and Engineering Technical Applications).

Figure 2-1. Component Elements of Engineering Learning

ENGINEERING HABITS OF THE MIND	ENGINEERING PRACTICES	ENGINEERING KNOWLEDGE
• Optimism • Persistence • Collaboration • Creativity • Conscientiousness • Systems Thinking	• Engineering Design • Material Processing • Quantitative Analysis • Professionalism	• Engineering Sciences • Engineering Mathematics • Engineering Technical Applications

Table 2-1: P-12 Engineering Content Taxonomy

ENGINEERING HABITS OF MIND	**OPTIMISM**	Engineering-literate individuals , 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. (NAE, 2019)
	PERSISTENCE	Failure is expected, even embraced, as engineering-literate individuals 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. (NAE, 2019)
	COLLABORATION	Engineering successes are built through collaboration and communication. Teamwork is essential. Engineering-literate individuals are willing to work with others. They are skilled at listening to stakeholders, thinking independently, and then sharing ideas. (NAE, 2019)
	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 engineering-literate individuals excel. Finding new ways to apply knowledge and experience is essential in engineering design and is a key ingredient of innovation. (NAE, 2019)
	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 i the moral issues that may arise from the work. (NAE, 2019).
	SYSTEMS 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, engineering-literate individuals need to be able to recognize and consider how all those different systems are connected. (NAE, 2019)

ENGINEERING PRACTICES	**ENGINEERING DESIGN**	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)
	MATERIAL PROCESSING	Material Processing is the practice that engineering-literate individuals use to convert materials into products, often referred to as making. 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.
	QUANTITATIVE ANALYSIS	Quantitative Analysis is the practice that engineering-literate individuals use to support, accelerate, and optimize the resolution of 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.
	PROFESSIONALISM	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 design decisions that protect the public's well-being, improve society, and mitigate negative impacts on the environment.

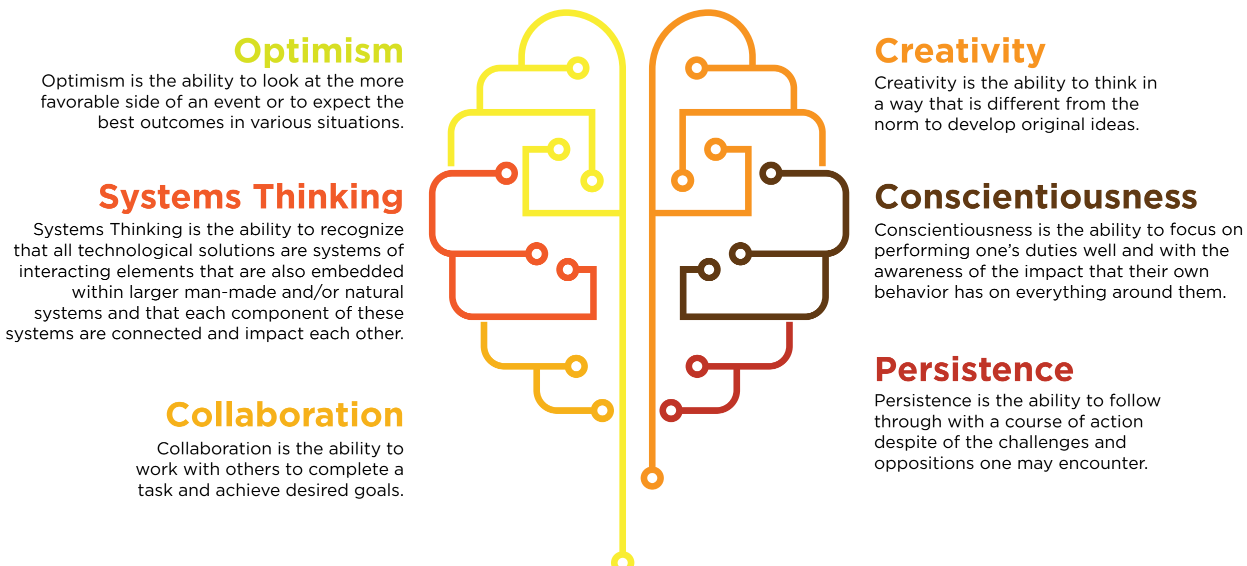
ENGINEERING KNOWLEDGE	**ENGINEERING SCIENCES**	Engineering Science is a knowledge base consisting of the basic principles and laws of the natural world that engineering professionals draw upon to complete engineering tasks.
	ENGINEERING MATHEMATICS	Engineering Mathematics is a knowledge base consisting of practical mathematical techniques and methods that engineering professionals apply within industry and research settings to better solve problems and complete engineering tasks in a predictive manner.
	ENGINEERING TECHNICAL APPLICATIONS	Engineering Technical Applications is an interdisciplinary knowledge base consisting of the practical engineering principles necessary to bring ideas to reality and to operate and carry out technical analyses of tangible engineering outputs.

It is important to note that the *Engineering Habits of Mind* and the concepts related to the *Engineering Practices* should be viewed as "core" and deemed essential to achieve *Engineering Literacy.* However, the concepts related to *Engineering Knowledge* should be viewed as auxiliary in nature, as they are to be leveraged, when appropriate, to inform engineering practice and situate learning experiences within authentic contexts. The following sections will dive deep into each of the dimensions of engineering learning.

Dimension 1: Engineering Habits of Mind

The *Engineering Habits of Mind* are the traits or ways of thinking that influence how a person views the world and reacts to everyday challenges (see Figure 2-2). These habits should become engrained within a students' everyday cognizance and allow them to effortlessly, efficiently, and autonomously devise solutions to problems or develop improvements to current technologies, processes, and practices (Royal Academy of Engineering [RAE], 2017). As the *Engineering Habits of Mind* are developed, they should become students' automatic response to any engineering-related activity or problem-solving scenario, enabling them to pursue a specific goal that is aimed toward a learning breakthrough or technological success (Lally and Gardner, 2013; Wood and Runger, 2016).

Figure 2-2. Engineering Habits of Mind



As stated by the Royal Academy of Engineering (2017), cultivating or transforming one's habits requires a clear description of what the desired habits are and how they are formed. Therefore, the following sections describe the six habitual ways of thinking in which students should be provided the opportunity to develop within the context of engineering. As habit formation is a gradual and incremental process, students should be provided the opportunity to develop these *Engineering Habits of Mind* through constant repetition of the habitual actions within a relevant and authentic context, along with the provision of an appropriate reward (Lally and Gardner 2013; RAE, 2017; Wood and Runger, 2016) at each grade level.

As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should orient themselves to an engineering way of thinking by developing the *Engineering Habits of Mind.* These *Engineering Habits of Mind* are:

Optimism is the ability to look at the more favorable side of an event or to expect the best outcomes in various situations. It allows a person to view challenging situations as opportunities to learn and improve or as chances to develop new ideas. An optimistic habit of mind enables a person to be persistent in looking for the optimal solutions to problems. This *Engineering Habit of Mind* is important because engineering-literate individuals will often experience repeated failures or unfavorable situations when solving a problem. An optimistic way of thinking provides ongoing motivation to focus on successfully resolving the problem at hand. Engineering-literate individuals, 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 (NAE, 2019).

> As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be able to maintain an **optimistic** outlook throughout the course of an engineering project/activity in order to persevere in accomplishing designated tasks.

Persistence is the ability to follow through with a course of action despite of the challenges and oppositions one may encounter. This ability also allows a person to continuously look for improvements in their operations. A persistent habit of mind enables an engineering-literate individual to develop optimal solutions to problems and see a project to its completion, as well as meet established goals and deadlines. This *Engineering Habit of Mind* is important, as failure is expected, even embraced, as engineering-literate individuals work to optimize a solution to a particular challenge. Engineering, particularly engineering design, is an iterative process. It involves trying and learning and trying again (NAE, 2019).

> As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be **persistent** throughout the course of an engineering project/activity in order to meet the project's objectives, uphold established deadlines, and be accountable for developing viable solutions to the problems they and others face.

Collaboration is the ability to work with others to complete a task and achieve desired goals, which includes effective *Communication* abilities. A collaborative habit of mind enables an engineering-literate individual to connect with, and draw upon, the perspectives, knowledge, and capabilities of others to best achieve a common purpose. This *Engineering Habit of Mind* is important to *Engineering Literacy,* as most engineering projects are undertaken as a team and successful solutions require the participation from team members with diverse backgrounds. Engineering successes are built through a willingness to work with others, listen to stakeholders, think independently, and communicate ideas collaboratively (NAE, 2019).

> As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be **collaborative/communicative** throughout the course of a team-based engineering project/activity to leverage diverse perspectives in successfully completing designated tasks.

Creativity is the ability to think in a way that is different from the "norm" in order to develop original ideas. A creative habit of mind enables an engineering-literate individual to perceive the world in novel ways, to find unknown patterns, and make new connections between seemingly unrelated information, in an effort to develop innovative ideas or solutions to problems. This *Engineering Habit of Mind* is important to *Engineering Literacy,* as finding new ways to apply knowledge and experience is essential in engineering practice and is a key ingredient of innovation. When everyone thinks exactly the same way there can be a lack of technological and societal advancement (NAE, 2019).

WHAT IS ENGINEERING LITERACY?

To ensure that all have the opportunity to become engineering-literate individuals, it's important to have a clear definition and defined educational goal. Our community defines this as the confluence of content knowledge, habits, and practices merged with the ability to communicate, think, and perform in a way that is meaningful within the context of engineering and the human-made world.

As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be **creative** throughout the course of an engineering project/activity, through the repetitive use of creativity strategies and tools, to develop innovative solutions to the problems they and others face.

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. A conscientious habit of mind enables an engineering-literate individual to maintain the highest standards of integrity, quality, ethics, and honesty when making decisions and developing solutions to ensure the public's safety, health, and welfare. This Engineering Habit of Mind is important to *Engineering Literacy* as engineering has a significant ethical dimension. The technologies and methods that engineering-literate individuals 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 one's work (NAE, 2019).

As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be **conscientious** when making decisions throughout the course of an engineering project/activity, through repetitive questioning and critiques, to develop ethical solutions to the problems they and others face.

Systems Thinking is the ability to recognize that all technological solutions are systems of interacting elements that are also embedded within larger human-made and/or natural systems and that each component of these systems are connected and impact each other. A systems-thinking habit of mind enables engineering-literate individuals to understand how each component of a solution design or idea fits with other components while forming a complete design or idea. Additionally, it enables them to consider how a solution idea or design interacts as a part of the larger human-made and/or natural systems in which they are embedded. This *Engineering Habit of Mind* is important to *Engineering Literacy,* as 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, engineering-literate individuals need to be able to recognize and consider how all those different systems are connected (NAE, 2019).

As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be able to think in terms of **systems** when making decisions throughout the course of an engineering project/activity, through recurring design critiques, in order to consider how a solution idea or design interacts with and impacts the world.

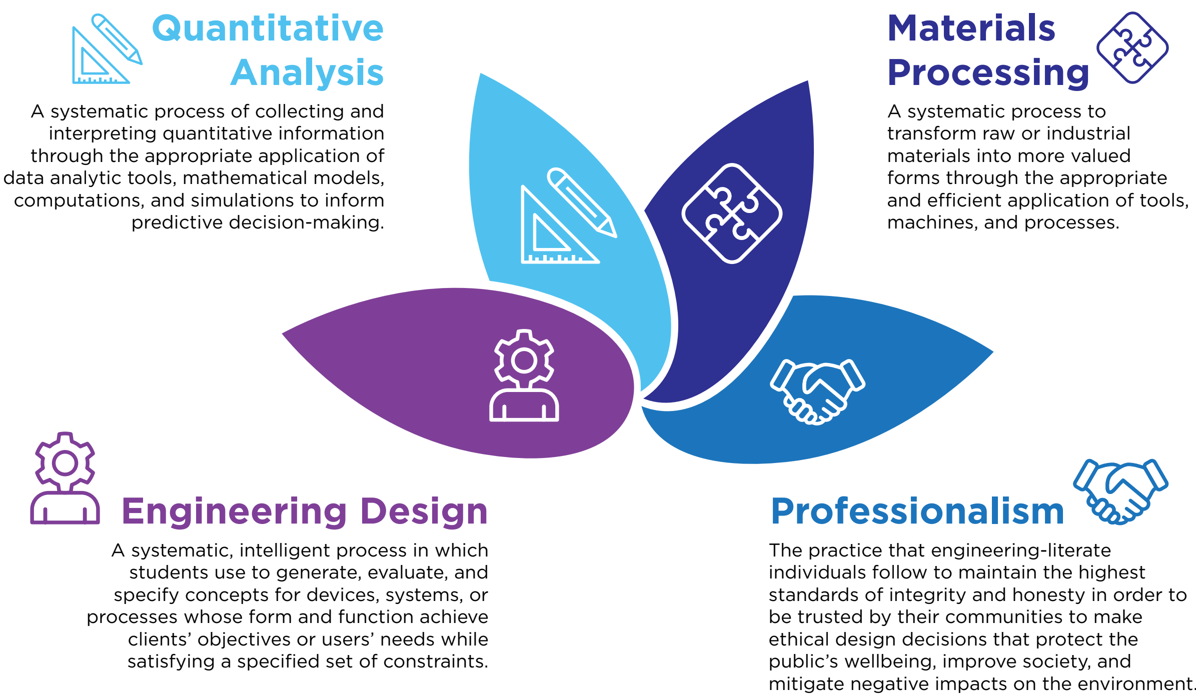
ENGINEERING LEARNING: A NATIONAL IMPERATIVE

We must continue to collaborate to provide the resources necessary to support all schools, not just those with abundant resources, and to offer engineering learning experiences as an opportunity for all students, rather than an amenity for the few. By defining the outcome of engineering literacy, education stakeholders can then outline the content that teachers will need to be prepared to teach and develop the learning pathways toward a distinct academic goal. This can be one step toward democratizing engineering learning across grades P-12 and advancing the nation's technological and innovative output designed for the whole of society.

Dimension 2: Engineering Practices

Engineering Practices are the combination of skills and knowledge that enable a student to authentically act or behave like an engineering-literate individual (see Figure 2-3). The core concepts of engineering practice should represent the knowledge associated with performing a particular practice well and with increased sophistication. Competence in these practices builds over time with multiple experiences. This framework is oriented around four comprehensive and fundamental practices: (1) *Engineering Design,* (2) *Material Processing,* (3) *Quantitative Analysis,* and (4) *Professionalism.* Each fundamental practice will be described in the following sections and detail what students should master by the end of secondary school in order to be engineering literate.

Figure 2-3. Engineering Practices



As a goal of P-12 Engineering Learning, 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). While this practice is often depicted as a step-by-step process, in actuality it is often a messy, iterative, and complicated practice that follows no set procedure. As such, this practice can involve a variety of methods and techniques that require a wide range of knowledge. Therefore, competency in this practice requires knowledge of core concepts such as problem framing, decision-making, ideation, project management, design methods, and prototyping.

As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be able to demonstrate competence in the practice of *Engineering Design* by:

- constructing justified problem statements that highlight the key elements of a design scenario, including multiple perspectives, to guide the evaluation of trade-offs between multiple, and sometimes conflicting, goals, criteria, and constraints during a design project (***Problem Framing***).

- collecting, evaluating, and synthesizing data and knowledge from a variety of sources to inform their design process (***Information Gathering***).

- generating multiple innovative ideas through both divergent- and convergent-thinking processes while communicating and recording ideas in two- and three-dimensional sketches using visual-spatial techniques (***Ideation***).

- building a prototype of an idea using the appropriate tools and materials for the desired prototype fidelity level while establishing the appropriate testing/data collection procedures to improve their design (***Prototyping***).

- making informed (data/evidence/logic-driven) choices within a design scenario through the application of *Engineering Knowledge* and the utilization of decision-making tools to converge on one decision within a team setting (***Decision-Making***).

- planning and managing a design project to achieve the desired goals within the established constraints through the application of appropriate project management strategies and techniques (e.g., team charters, Gantt charts) (***Project Management***).

- developing a plan to manage an engineering project through the appropriate application of a specified design strategy (***Design Methods***).

- interpreting, analyzing, and creating graphical representations of a design idea following commonly accepted conventions (***Engineering Graphics***).

- articulating their ideas, decisions, and information throughout and at the conclusion of a design project, with the consideration of the target audience through a variety of verbal and visual communication strategies and tools (***Design Communication***).

Material Processing is the practice that engineering-literate individuals use to convert materials into products, often referred to as *making* (see Guiding Principle *Leverage Making as a Form of Active 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 measurement and precision, fabrication, material classification, and safety.

As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be able to demonstrate competence in the practice of *Materials Processing* by:

- designing a product in such a way that it is easy to produce and then making the product by applying appropriate manufacturing processes (***Manufacturing***).

- selecting the appropriate measurement devices and units and then applying them with precision to design, produce, and evaluate quality products (***Measurement & Precision***).

- choosing the appropriate tools, processes, techniques, equipment, and/or machinery to make a reliable, quality product/system based on a plan or workable approach to meet the specified design criteria of a customer in accordance with engineering standards (***Fabrication***).

- distinguishing between different materials in terms of their structures and properties and determine how to apply the materials to design/create quality products in a suitable and safe manner (***Material Classification***).

- using knowledge of casting/molding/forming to inform their decisions when developing a design as well as to physically change the shapes of materials (***Casting/Molding/Forming***).

- using knowledge of separating and machining to inform their decisions when developing a design as well as to physically change the shapes of objects by removing excess material (***Separating/ Machining***).

- using knowledge of joining methods to inform their decisions when developing a design as well as to physically assemble parts into a quality product (***Joining***).
- using knowledge of conditioning and finishing methods to inform their decisions when developing a design as well as to physically produce a quality end product (***Conditioning/Finishing***).
- safely, responsibly, and efficiently processing materials within a working environment without causing harm or injury to themselves or others (***Safety***).

Quantitative Analysis is the practice that engineering-literate individuals use to support, accelerate, and optimize the resolution of 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 *Strive for Authenticity in Engineering*). Competency in this practice requires knowledge of core concepts such as computational thinking, computational tools, and data collection, analysis, and communication.

As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be able to demonstrate competence in the practice of *Quantitative Analysis* by:

- designing, developing, implementing, and evaluating algorithms/programs that are used to visualize/control physical systems that address an engineering problem/task (***Computational Thinking***).
- selecting and using the appropriate computational tools to analyze quantitative data related to an engineering problem to communicate/ predict the effectiveness of a solution design (***Computational Tools***).
- selecting and implementing the most appropriate method to collect and analyze quantitative data and then make, justify, and share a conclusion based on the analysis (***Data Collection, Analysis & Communication***).
- analyzing an engineering system through identifying its inputs, outputs, processes, and feedback loops to implement controls to predict and optimize system performance (***System Analytics***).

WHAT ARE THE ATTRIBUTES OF AN ENGINEERING LITERATE STUDENT?

A engineering literate individual 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.

- developing and using a variety of models to simulate, evaluate, improve, and validate design ideas (***Modeling & Simulation***).

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.

As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be able to demonstrate competence in the practice of *Professionalism* by:

- interpreting the engineering code of ethics in an effort to make ethical decisions while engaged in an engineering project (***Professional Ethics***).
- establishing the appropriate work culture among team members in order to maintain honesty and integrity within an engineering project (***Workplace Behavior/ Operations***).
- leveraging the work of others, while protecting their own, following appropriate and ethical conventions related to intellectual property (***Honoring Intellectual Property***).
- analyzing the potential impacts of their decisions within an engineering project, considering a variety of nontechnical concerns, to evaluate their work in respect to relevant societal issues (***Technological Impacts***).
- evaluating the interactions between engineering activities and society in order to create solutions to engineering problems that consider the voice, culture, needs, and desires of the people that the solution touches (***Role of Society in Technological Development***).
- appraising engineering-related careers and the general requirements of the associated employment opportunities to create a long-term plan to pursue their career goals, whether it be engineering related or not (***Engineering-Related Careers***).

ENGINEERING LEARNING GOALS:

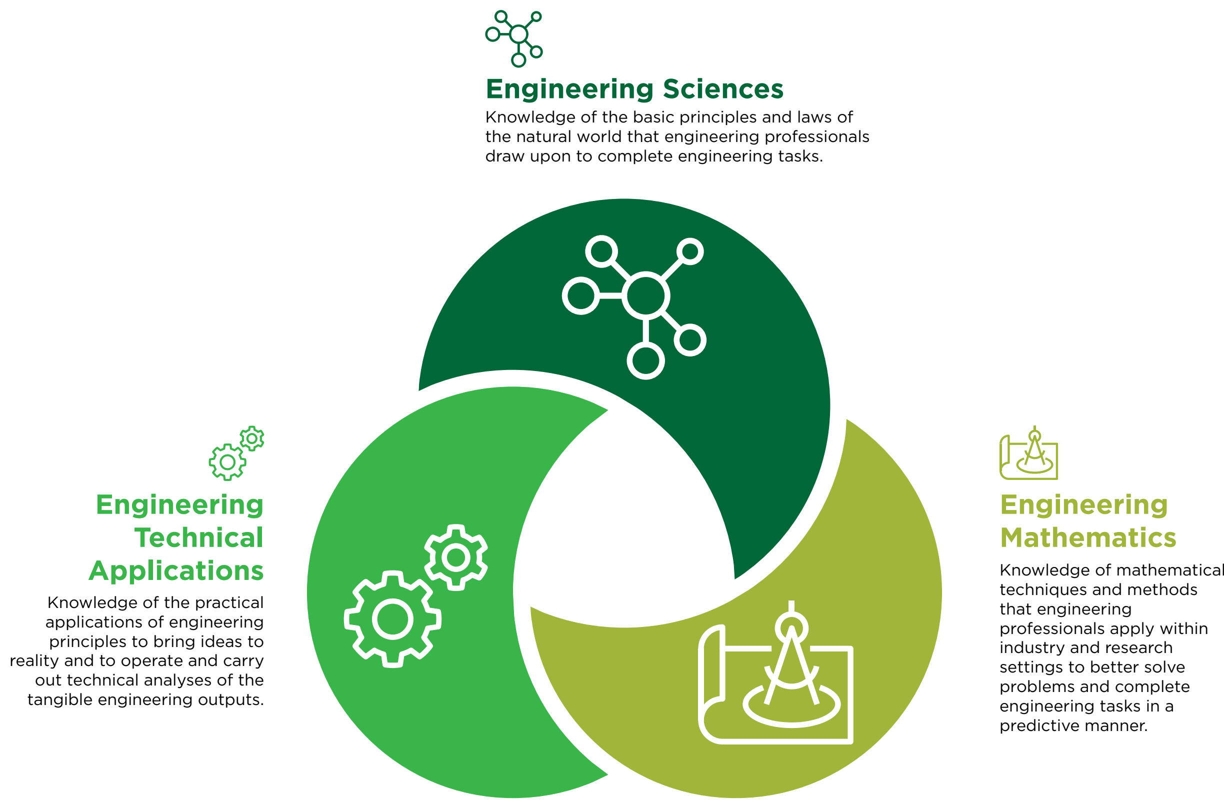
The goal of Engineering Learning is to:

1. cultivate the habits of mind necessary to orient students to an engineering way of thinking,
2. engage students in the authentic practices of engineering to resolve real challenges, and
3. support students in appreciating, acquiring, and applying, when appropriate, scientific, mathematical, and technical concepts in relevant ways to better perform their engineering practice and resolve the problems they encounter.

Dimension 3: Engineering Knowledge

Engineering is often considered the practical application of science, mathematics, and technical know-how to effectively and efficiently solve problems through the design, development, and evaluation of products, processes, systems, and structures. Therefore, and in addition to the broad set of competencies related to the *Engineering Practices,* a strong understanding of mathematical, scientific, and technical concepts is essential to solve such problems (see Figure 2-4). Accordingly, one dimension of engineering literacy is *Engineering Knowledge,* which consists of the concepts that are necessary to situate one's habits and practices in a conceptual domain. However, the *Engineering Knowledge* dimension is defined as concepts that students should recognize and be able to draw upon when appropriate. While there are many disciplines and sub-disciplines of engineering, engineering-literate individuals have similar qualities, such as competence in the *Engineering Practices* (Engineering Design, Material Processing, Quantitative Analysis, and Professionalism) as well as a knowledge base in the scientific, mathematical, and technical domains. Therefore, this framework posits that *Engineering Knowledge* spans three broad domains: (1) *Engineering Sciences,* (2) *Engineering Mathematics,* and (3) *Engineering Technical Applications.* However, by the end of secondary school one would not expect a student to fully understand the entirety of these areas in depth. But to be engineering-literate individuals, they should be able to deploy their engineering practices and engineering habits of mind to acquire and apply the knowledge necessary to complete engineering tasks. Accordingly, the concepts for the knowledge dimension are labeled as "auxiliary concepts."

Figure 2-4. Engineering Knowledge Domains



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 and in Appendix A as a starting point to align with the overall intent of this framework.*

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 domains. 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/or (3) guide the development of engineering programs.*

As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be able to recognize and, when appropriate, apply domain-specific Engineering Knowledge to inform their engineering practice. These knowledge domains are:

Engineering Science is a knowledge base consisting of the basic principles and laws of the natural world that 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, and different solution approaches may draw on a student's knowledge gained from a variety of domains. In P-12 classrooms students should engage in experiences that position *Engineering Sciences* as a way to inform their *Engineering Practice.*

Therefore, 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* concepts could be drawn upon to help students solve problems in a manner that is analytical, predictive, repeatable, and practical. For example, students should be able to recognize and, when appropriate, draw upon knowledge of:

- **Statics** content, such as (a) *determining the resultants of force systems,* (b) *finding equivalent force systems,* (c) *conditions of equilibrium for rigid bodies,* (d) *the analysis of frames/trusses,* (e) *finding the centroid of an area,* and (f) *calculating area moments of inertia,* to analyze the forces within a static system in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Mechanics of Materials,** such as (a) *stress types and transformations,* (b) *material characteristics,* (c) *stress-strain analysis,* and (d) *material deformations,* to analyze the properties, compositions, and behaviors of available or needed materials in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Dynamics** content, such as (a) *kinetics,* (b) *kinematics,* (c) *mass moments of inertia,* (d) *force acceleration,* (e) *impulse momentum,* and (d) *work, energy, and power,* to analyze the forces within a dynamic system in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Thermodynamics** content, such as (a) the *Laws of Thermodynamics,* (b) *equilibrium,* (c) *gas properties,* (d) *power cycles and efficiency,* and (e) *heat exchangers,* to analyze the forces within an energy system in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Fluid Mechanics** content, such as (a) *fluid properties,* (b) *lift, drag, and fluid resistance,* (c) *pumps, turbines, and compressors,* (d) *fluid statics and motion (Bernoulli's Equation),* and (e) *pneumatics and hydraulics,* to analyze how fluids behave and measure/control their flow in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Heat Transfer** content, such as (a) *conductive, convective, and radiation heating* and (b) *heat transfer coefficients,* to analyze how heat moves from one system (solid, liquid, or gas) to another in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Mass Transfer & Separation** content, such as (a) *molecular diffusions,* (b) *separation systems,* (c) *equilibrium state methods,* (d) *humidification and drying,* (e) *continuous contact methods,* and (f) *convective mass transfer,* to analyze the mechanism of transfer due to difference in concentrations in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Chemical Reaction & Catalysis** content, such as (a) *reaction rates, rate constants, and order,* (b) *conversion, yield, and selectivity,* (c) *chemical equilibrium and activation energy,* and (d) *fuels,* to analyze the factors influencing the processes of reaction and catalysis with mathematical models in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Circuit Theory** content, such as (a) *series and parallel circuits,* (b) *Ohm's Law,* (c) *Kirchhoff's Laws,* (d) *resistance, capacitance, and inductance,* (e) *wave forms,* (f) *signals,* and (g) *current, voltage, charge, energy, power, and work,* to design, and mathematically justify, an electrical circuit in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Engineering Mathematics is a knowledge base consisting of practical mathematical techniques and methods that 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 concepts related to *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, and different solution approaches may draw on a student's knowledge gained from a variety of knowledge domains. In P-12 classrooms, students should engage in experiences that position *Engineering Mathematics* as a way to inform their engineering practice.

Therefore, by the end of secondary school, engineering-literate students should be able to recognize and apply *Engineering Mathematics* concepts to inform their engineering practice. The following *Engineering Mathematics* concepts could be drawn upon to help students solve problems in a manner that is analytical, predictive, repeatable, and practical. For example, students may be able to recognize and, when appropriate, draw upon knowledge of:

- **Algebraic** content and practices, such as (a) *the basic laws of algebraic equations,* (b) *reasoning with equations and inequalities,* (c) *representing equations in 2D and 3D coordinate systems,* and (d) *linear algebra,* to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Geometric/trigonometric** content and practices, such as (a) *geometric measurement and dimensions,* (b) *expressing geometric properties with equations,* (c) *right triangles,* (d) *trigonometric functions,* and (e) *vector analysis,* to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Statistics/probability** content and practices, such as (a) *probability distributions,* (b) *descriptive statistics and measures of central tendencies (mean, median, mode),* (c) *inferential statistics and tests of significance,* and (d) *using probability to make decisions,* to evaluate/justify solutions to problems in a manner that is analytical, predictive, repeatable, and practical.

- **Calculus** content and practices such as (a) *derivatives,* (b) *integrals,* (c) *differential and integral equations,* and (d) *vectors, including dot and cross products,* to solve problems in a manner that is analytical, predictive, repeatable, and practical

Engineering Technical Applications is an interdisciplinary knowledge base consisting of the practical engineering principles necessary to bring ideas to reality and operate and carry out technical analyses of 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 Technology* knowledge base is essential, as engineering tasks are typically open-ended and ill-defined, and different solution approaches may draw on a student's knowledge gained from a variety of domains.

Therefore, by the end of secondary school, engineering-literate students should be able to recognize and apply *Technical* engineering concepts to inform their engineering practice. The following *Technical* engineering concepts could be drawn upon to help students solve problems in a manner that is analytical, predictive, repeatable, and practical. For example, students may be able to recognize and, when appropriate, draw upon knowledge of:

- **Mechanical Design** content, such as (a) *machine elements/mechanisms,* (b) *manufacturing processes,* and (c) *machine control,* to forecast and validate the design performance of a mechanism or machinery component in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Structural Analysis** content, such as (a) *the physical properties of construction materials,* (b) *material deflection,* (c) *material deformation,* (d) *column and beam analysis,* and (e) *the implementation of design codes,* to evaluate the structural elements of a structure design using the proper formulas and conventions necessary to calculate the effects of applied stresses or strains.

- **Transportation Infrastructure** content, such as (a) *street, highway, and intersection design,* (b) *transportation planning and control (including safety, capacity, and flow),* (c) *traffic design,* and (d) *pavement design,* to plan/create facilities and systems that are needed to serve a country or community while considering of a variety of criteria and constraints about the safe and efficient movement of people and goods.

- **Hydrologic Systems** content, such as (a) *hydrology principles,* (b) *water distribution and collection systems,* (c) *watershed analysis processes,* (d) *open channel systems,* (e) *closed channel systems,* (f) *pumping stations,* and (g) *hydrologic field tests and codes,* to analyze/model the flow of water in and out of a system, using the appropriate mathematical equations and conventions in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Geotechnics** content, such as (a) *geological properties and classifications,* (b) *soil characteristics,* (c) *bearing capacity,* (d) *drainage systems,* (e) *slope stability,* (f) *erosion control,* (g) *foundations and retaining walls,* and (h) *geotechnical field tests and codes,* to analyze/model the behavior of Earth's materials, using the appropriate mathematical equations and conventions, in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

- **Environmental Considerations** content, such as (a) *ground and surface water quality,* (b) *wastewater management,* (c) *air quality,* and (d) *environmental impact regulations and tests,* in order to design methods to protect and manage our air, water, soil, and related ecosystems.

- **Chemical Applications** content, such as (a) *inorganic chemistry,* (b) *organic chemistry,* (c) *chemical, electrical, mechanical, and physical properties,* (d) *material types and compatibilities,* (e) *corrosion,* and (f) *membrane science,* to analyze and select, or propose a novel combination of, materials to produce a desired product or process.

- **Process Design** content, such as (a) *process controls and systems,* (b) *process flow, piping, and instrumentation diagrams,* (c) *recycle and bypass processes,* and (d) *industrial chemical operations,* to visually represent the procedures and facilities necessary to produce a desired product.

- **Electrical Power** content, such as (a) *motors and generators,* (b) *alternating and direct current,* (c) *electrical materials,* (d) *electromagnetics,* (e) *voltage regulation,* (f) *electricity transmission and distribution,* and (g) *magnetism,* to determine and justify which electrical materials are most appropriate for an engineering task involving electrical power systems, using mathematical equations and the correct units.

- **Communication Technologies** content, such as (a) *digital communication,* (b) *telecommunication,* (c) *graphic communication,* (d) *photonics,* and (e) *network systems,* to visually represent, analyze, and propose the procedures and products necessary to effectively, efficiently, and appropriately communicate data and/or information.

- **Electronics** content, such as (a) *electronic instrumentation,* (b) *electronic components (diodes, transistors, resistors, power supplies, capacitors, breadboards, etc.),* (c) *digital logic (integrated circuits, gates, flip-flops, counters, etc.),* and (d) *electrical diagrams/schematics,* to successfully choose different instrumentation, components, and materials to visually represent, analyze, design, and test an electronic device to perform a specific task.

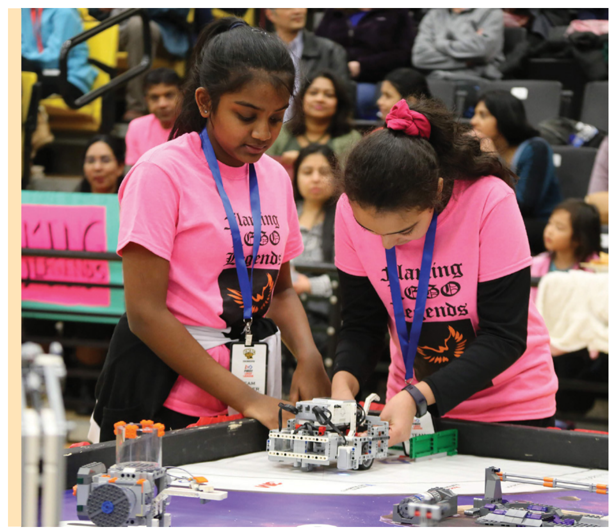
- **Computer Architecture** content, such as (a) *computer hardware,* (b) *computer operating software and applications,* (c) *memory,* (d) *processors and microprocessors,* and (e) *coding,* to visually represent how the components of a computer system relate to one another and how to configure the components for desired performance.

Summary

This chapter, in combination with **Appendix A,** provides a comprehensive definition of the three dimensions of engineering learning and provides 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, so that all children have the opportunity to engage in rigorous engineering experiences that enable them to think, act, and learn like an engineer. While this chapter does not specify grade bands for the habits, practices, and concepts of engineering, it does provide endpoints for each component idea that describes the understanding that students should have acquired by the end of secondary school. Moreover, the sub-concepts for high school engineering, provided in Appendix A, add detail for each concept related to the *Engineering Practices* and *Engineering Knowledge* and can help to provide the content necessary for drafting a hypothetical roadmap or engineering performance matrix. Also, this framework posits that *Engineering Literacy* should be developed across the span of the P-12 years, more explicitly developing *Engineering Habits of Mind* at the early grades and moving toward more explicitly developing *Engineering Knowledge* at the higher grades, all while developing competence in *Engineering Practice.*

AN ENGINEERING LESSON PLAN MODEL:

Engineering Learning should be embedded within projects and activities that offer opportunities for children to exercise informed engineering practices, with increased sophistication over time, in socially relevant and culturally situated contexts that build connections to their lives and communities.



HOW TO DEFINE ENGINEERING LEARNING?

Engineering learning is three-dimensional 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 Practice.

Chapter III

Diversity, Equity, & Inclusion throughout P-12 Engineering Learning

A core principle of the *Framework for P-12 Engineering Learning* is to ensure all students are exposed to a high-quality engineering learning experience. Regardless of resources, schools should have the ability to equally and equitably serve each student under their tutelage. Specifically, a commitment to increasing the participation, inclusion, and empowerment of underrepresented student groups in all formal and informal engineering learning should be made. Such efforts are critical for achieving the goal of *engineering literacy for all* and ensuring that every child can act, think, and learn like an engineer. As stated by the American Society of Engineering Education (ASEE), diversity and inclusiveness are essential to cultivating educational experiences and innovations that drive the development of creative solutions in addressing the world's challenges. Moreover, such deliberate efforts will address the well-documented equity and achievement gaps that exist across a variety of demographics.

While engineering has been at the forefront of the technological advances of our world, there have been consistent social consequences in terms of equity that can be attributed to the limited opportunities for all to develop their engineering literacy and to the lack of diversity of those involved in engineering practice. Of greater significance is that without deliberate efforts to be inclusive, "history has shown that new technologies benefiting one part of society sometimes have less fortunate impacts on other segments" (ASEE & SEFI, 2020, page 1). Therefore, this chapter will detail approaches for promoting diversity, equity, and inclusion through the implementation of P-12 engineering learning. Such approaches, informed by the engineering education community during the development of this framework, can increase the ability to serve *all* students, especially those historically and systemically underserved. The result is improving the critically needed diversity of the workforce, advancing the technological and innovative output of our nation, and perhaps most important, supporting a more robust and democratic community. This type of effort requires that equity be the kernel of any engineering learning effort, whether at the policy level or at the school level of instruction (K-12 Computer Science Framework, 2016; Marshall and Berland, 2012). Consequently, it is important that educational strategies, such as culturally relevant pedagogy, are not just considered an addendum to engineering curriculum and instruction (Clausen and Greenhalgh, 2017). Instead, they must be naturally integrated into the processes of content development, knowledge construction, unconscious bias elimination, pedagogical practice, and school culture (Banks, 2007).

To follow the recommendations of the P-12 engineering learning community and to adhere to the framework's guiding principles, this document centers around four main approaches to help address diversity, equity, and inclusion in the implementation of engineering learning:

- Establishing Coherence and Articulation between Engineering Concepts
- Connecting Engineering Learning with Student Culture, Community, Family, Interest, and Society
- Including Core Concepts related to the Roles/Influences of Culture and Society in Engineering
- Modeling Contextualized Learning Experiences that are Socially Relevant and Culturally Situated

First, thoughtful consideration was given to establishing coherent engineering concepts that support the development of engineering literacy (see Chapter 2 and Appendix A). The underlying intent is to ensure that all students are provided comparable opportunities to support the development of similar competencies. Providing consistency in the design of engineering literacy performance expectations can ensure that any curriculum or standards reflect all the key stages in engineering learning. This uniformity can ensure that additional out-of-school opportunities, which many students lack access to, are not necessary to achieve engineering literacy. By defining the outcome of engineering literacy (i.e., what students should think, know, and be able to do by the end of secondary school), educational stakeholders can then outline the content that teachers will need to be prepared to teach and develop the learning pathways toward a distinct educational goal.

Second, this framework includes core concepts related to teaching students about diversity and the roles/influences that culture and society have within technological development. This approach can position learning experiences to explore and value different perspectives and support students in devising innovative solutions to complex challenges that serve the whole of society.

Third, the framework provides recommendations for educators to develop and implement curricula and instruction in a manner that connects engineering learning with students' cultures, communities, families, interests, and society as a whole, in an attempt to develop a sense of belonging within, and personal relevance to, engineering.

Lastly, the framework provides examples of how to inclusively introduce engineering content within the framework to plan lessons and develop activities that are socially relevant and culturally situated. These examples were developed by the framework community and informed through pilot implementation sites.

While the approaches outlined in this chapter can help educators develop a mindset toward creating engineering learning experiences that reach more students, supporting diversity, equity, and inclusion requires long-term commitments from all educational stakeholders. This is critical to build a culture of engineering learning that represents, values, and celebrates different perspectives and serves the whole of society. As a result, any related educational initiatives resulting from the framework must actively support inclusive learning environments in which all students are welcomed, respected, and valued.

Equitable Engineering Learning for ALL Students

The purpose of equity in engineering learning is not to prepare every student to major in engineering and go on to engineering-related careers. Rather, it is about equity in access, participation, and achievement. Ensuring that all students have the opportunities to develop habits, knowledge, and practices will enable individuals to productively participate in today's world, make informed decisions about their lives, and be successful in an engineering career if they choose to pursue one (Marshall and Berland, 2012). If equity can exist, then there should be appropriate supports based on individual students' needs, so that all have the opportunity to achieve the same levels of success.

Inherent in this goal is a comprehensive expectation of academic success that is accessible by, and applies to, every student (K-12 Computer Science Framework, 2016). As such, engineering curriculum and instruction plays a significant role in providing the experiences for all students to engage with the engineering content and concepts highlighted in this framework, and in addressing misperceptions about engineering-related careers. For example, Mehalik, Doppelt, and Schunn (2008) documented that nuances in implementation of STEM curricula (e.g., choice in design, ownership of ideas, equal access to materials) correlate to closing or widening equity gaps. Additional resources, such as the *STEM Equity Program Evaluation Rubric,* a tool developed by Lufkin, Mitchell, and Thackeray (2019) to evaluate the factors that influence access and success for underrepresented students in STEM education, can be used to ensure that engineering learning experiences are equitable for students. Lufkin, Mitchell, and Thackeray go on to stress that "serving 'all students' does not ensure equity, so considering how each of these attributes impacts underrepresented students in STEM and addressing those barriers will create a STEM learning environment where every student can succeed". By combining the attributes in the *STEM Equity Program Evaluation Rubric* with the Framework for P-12 Engineering Learning, educators can ensure each and every student is served.

In addition, efforts should be made to embed engineering learning within projects and activities that offer opportunities for children to exercise informed engineering practices with increased sophistication in **socially relevant** and **culturally situated** contexts that build connections to their lives (Scriven, 2019) and provide a sense of belonging within the realm of engineering. While we recognize that this approach will not promote equity on its own, we do believe it is seminal for planning engineering learning experiences with a focus on connecting with and valuing the community and culture of one's students.

Through socially relevant and culturally situated learning, students can be afforded the opportunity to construct personal relationships with the **Engineering Habits of Mind, Engineering Knowledge, and Engineering Practices** and ultimately believe engineering is relevant to their lives. The use of relevant engineering contexts can also have benefits such as counteracting barriers to broadening participation in engineering learning as well as to careers. When a student sees how aspects of their culture and community are related to engineering habits, concepts and practices, reduction in identity conflicts with the discipline can occur. Students may then begin to feel like their personal or cultural identity is compatible with participation in engineering (Eglash, Bennett, O'Donnell, Jennings, and Cintorino, 2006), which may also result in substantive content learning (Rahm, 2002; Warren, Ballenger, Ogonowski, Rosebery, and Hudicourt-Barnes, 2001) and increased educational engagement (Buxton, 2005; Basu and Calabrese Barton, 2006; Scriven, 2019).

Socially relevant and culturally situated contexts can also offer opportunities for integrating engineering with the study of culture and diversity and other academic subjects, specifically the humanities. For example, one of the core concepts within this framework involves understanding the *Role of Society in Technology Development.* This concept highlights learning about how engineering is influenced by people's social and cultural interactions at the local and global community levels, which can (a) link learning with other fields of study, (b) enable students to investigate other cultures and communities, and (c) engage them in work that can make a difference in others' lives. Also, this mindful approach can enable students to make informed decisions that are sensitive to cultural values and perspectives when engaging in engineering tasks and that take into consideration the societal impacts of any engineering solutions.

While these efforts can be impactful, engaging all students in engineering learning can be a challenge. Students each have different backgrounds, motivations, and goals for their learning. Therefore, more work is necessary for teachers and local curriculum coordinators to reach students who may not view engineering as an engaging opportunity to obtain their goals. For example, students who are interested in healthcare, nursing, physical therapy, generally helping people, or in other "seemingly" non-engineering pursuits such as athletics, may be influenced by the social responsibility contexts provided through engineering. As an example, the content in the framework can be leveraged to introduce engineering through current issues, such as athletic concussion injuries, chronic traumatic encephalopathy, and the use of magnetic resonance imaging diagnosis, as a way to engage students interested in healthcare or athletics who may typically be unengaged with the thought of engineering learning and potential engineering-related career pathways (see Figure 3-1). In another example, engineering can also offer the opportunity to be involved in athletics in a way that makes them safer and improves the athletic experience. Waldrop et al. (2018) presents an example lesson that employs a culturally situated design context to intentionally teach students about the engineering concepts involved in material selection and the application of dynamics while engaging them in discussions about diversity and inclusion. In their example, students are challenged to develop athletic helmets that account for cultural attire, customs, and the various needs of diverse populations (see Figure 3-2).

Figure 3-1. Socially Relevant Context Example

SOCIALLY RELEVANT PROBLEM

Chronic Traumatic Encephalopathy

Krause, Strimel, and Rispoli (2018) provide an example of a socially relevant lesson that introduces students to biomedical engineering and teaches them related engineering concepts through problems associated with athletic concussions and head injuries. Concussive and sub-concussive injuries from contact sports can lead to severe brain damage and neurodegenerative diseases such as chronic traumatic encephalopathy (CTE). Relatively little is known about the connection between concussive injury and CTE, as current methods of definitive diagnosis require the dissection of the brain post-mortem. However, biomedical engineering breakthroughs and new medical imaging technologies/techniques (including magnetic resonance imaging) can show promise in enabling medical professionals to explore these injuries *in vivo,* while the patient is still living. This socially relevant context may provide opportunities for more student to engage in engineering learning.

Figure 3-2. Culturally Situated Context Example

CULTURALLY SITUATED ENGINEERING CONTEXT

Engineering in Athletics:
Teaching Material Selection and the Application of Dynamics for Designing Head Protection

Waldrop et al. (2018) provide an example of a socially relevant lesson that employs a culturally situated design context to intentionally teach students about the engineering concepts involved in material selection and the application of dynamics while engaging in discussions about diversity. In this lesson, students work in groups to address the issues of designing athletic helmets to account for cultural attire, various customs, increased safety, size, versatility, and the use of eco-friendly materials/manufacturing processes. This includes designing for customers in a way that requires the consideration of different physical sizes, cultural values/beliefs, religious backgrounds, characteristics of different genders, and/or disabilities. Then students are tasked to gather existing knowledge of their customers, learn about people, investigate material classifications, and explore the properties of materials, design new helmets that account for the needs of their target populations, and present their design solutions to their peers. Their teacher, as well as their peers, then evaluates the designs to ensure the products have addressed the target customers' needs and/or cultural values, material limits, aesthetic considerations, and cost requirements.

As seen through these examples, engineering learning—a problem-based, transformational subject—immerses students in projects that focus on real-world and community problems for social good. This type of learning experience can help acknowledge, value, and build upon the rich cultural backgrounds that students bring to the classroom. As described by (Sealey-Ruiz, 2010):

> Culture is transmitted from generation to generation and is the shared perceptions of a group's values, expectations, and norms. It reflects the way people give priorities to goals, how they behave in different situations, and how they cope with their world and with one another. People experience their social environment through their culture. (p. 50)

Students' cultural backgrounds are embedded with funds of knowledge that are "historically accumulated and culturally developed bodies of knowledge and skills essential for household or individual functioning and well-being" (Moll, Amanti, Neff, and Gonzalez, 1992, p. 133), which can be celebrated and leveraged to develop an inclusive learning environment, teach about diversity, connect with students' prior knowledge, and to conceive innovative solutions to relevant problems that are used to teach engineering habits, concepts, and practices.

Developing Socially Relevant and Culturally Situated Activities

Creating and developing an educational setting that integrates student backgrounds and culture can be analogous to the practice of engineering in many ways. As stated by Clausen and Greenhalgh (2017), "just as each design problem has its own unique context that is critical for a successful solution, knowing the students in the classroom is the first step to reaching all students and meeting their needs," and to do so "one must dig below the surface and get to know who students are, both inside and outside of the classroom" (p. 18). As Ladson-Billings (1995) explains, teachers should learn about their students' interests, hobbies, cultural beliefs, families, and educational expertise to better plan lessons and classroom activities, and that sources of diversity can come from a variety of places, including gender differences, language, culture, exceptionalities, socioeconomic status, and diversity of experience. Thus, instructional design should begin with the anticipatory set, based upon the relationships teachers built. This understanding will guide the design challenges teachers choose, and allow for flexibility in identification of problems, over posing challenges to them. Allowing students to choose what they design may result in a reduction of equity gaps (Mehalik, Doppelt, and Schunn, 2008).

Following the recommendations set forth in the K-12 Computer Science Framework (2016), teachers can develop socially relevant and culturally situated learning experiences by (a) looking to their students' communities for examples of projects and applications of engineering learning that can intentionally teach desired engineering concepts, (b) carefully examining their students' experiences, confidence, and ability levels, and then (c) crafting learning experiences that appropriately scaffold learning for the students. This is important, as authentic, socially relevant projects are very complex, and their intense open-ended nature can oftentimes make it too difficult for beginners to engage in the related learning experience (Rader, Hakkarinen, Moskal, and Hellman, 2011). However, with careful consideration of one's students and the engineering learning goals, socially relevant and culturally situated curricula can hold promise for engaging all students (K-12 Computer Science Framework, Scriven, 2019).

For delivering this type of learning experience, Ladson-Billings (1994) describes culturally responsive teaching as having the following principles: (1) communicating of high expectations, (2) using active teaching methods, (3) a teacher serving as the facilitator, (4) inclusion of culturally and linguistically diverse students, (5) cultural sensitivity, (6) reshaping curriculum to respond to students, (7) including student-controlled classroom discourse, (8) leveraging small group instruction, and (9) maintaining academically related discourse. In doing so, teachers of engineering can build on what students already know, help them understand there is more than one way of knowing and doing, encourage them to embrace their culture through the love of learning, highlight their strengths and interests, give them confidence in addressing their weaknesses, provide learning opportunities about other student cultures, vary instruction based on the learners, and maintain a welcoming classroom environment.

Accordingly, one of the *Guiding Principles* of this framework requires educators and curriculum developers to make an ongoing effort to learn about students' interests, hobbies, cultural beliefs, and families to gain insights into how best to engage them in engineering learning. Through the process of creating this framework, the engineering learning community sought to specifically promote equity, diversity, and inclusion in engineering curriculum and instruction by providing educators with examples of socially relevant lessons/activities designed to intentionally teach students, in a culturally responsive manner, the engineering core concepts and sub-concepts that are detailed in this framework (see Chapter 2 for concepts and Appendix A for high school sub-concepts). To do so, the engineering learning community developed a modified *engineering design-based learning lesson plan* template (Grubbs and Strimel, 2015) that can support educators in (1) identifying the authentic and rigorous engineering concepts and sub-concepts that they need/wish to teach, (2) recognizing the progression in which to teach it, and (3) crafting socially relevant and culturally situated instructional activities. The *Engineering Lesson Plan Template* is provided to assist in the development of engineering lessons based on this framework (Appendix B). The following section provides one example of a lesson developed based on this framework (Reprinted with permission from ITEEA and Kim, Newman, Lastova, Bosman, and Strimel, 2018).

Example of a Socially Relevant and Culturally Situated Engineering Lesson

Lesson: Engineering the Reduction of Food Waste
Teaching Problem Framing & Project Management through Culturally Situated Learning

This example, created by Kim, Newman, Lastova, Bosman, and Strimel (2018), presents a culturally situated and socially relevant lesson designed to intentionally teach secondary students core concepts related to increasing sophistication in the **Engineering Practice** of *Engineering Design.* This specifically focuses on the core concepts of *Problem Framing and Project Management.* The lesson includes (a) class discussions to engage students in a socially relevant problem (food waste and sustainability) within a culturally situated context (connection between food and culture) and (b) an experiential, team-based design activity to provide students with opportunities to learn and apply two core concepts of *Engineering Design* (*Problem Framing and Project Management*). At the end of this lesson students are expected to be able to develop a problem statement by identifying explicit and implicit goals, determining the constraints involved in a given problem, and considering multiple perspectives in regards to the design scenario that help eliminate any perceived assumptions that unnecessarily limit the problem-solving process. Additionally, students will be able to plan and manage a design project by applying a variety of project management strategies.

A Culturally Situated Context: Food as Cultural Heritage

Food is an essential part of cultural heritage and ethnic/national identity, as it has its own meanings related to historical, social, economic, political, or religious backgrounds. Food allows one to personally experience another culture and learn about other people, places, and perspectives. In this context, bringing food-related topics into the classroom has been considered one way to teach cultural diversity. Therefore, topics related to food heritage could then be applied to a variety of educational activities, such as engineering design tasks, to help bring cultural relevance to learning.

A Socially Relevant Problem: Sustainable Packaging for Reducing Food Waste

Food waste has received increasing attention and is considered to be connected with various sustainability issues. In 2012 the National Resources Defense Council (NRDC) reported that up to 40 percent of food in the United States goes uneaten. Just in the food supply chains, Gunders (2017) describes that the process of growing, processing, transporting, and disposing of uneaten food has an annual estimated cost of $218 billion and produces more greenhouse gas emissions than 37 million cars. Beyond money and energy, raw materials used for the wasted food are squandered. The United Nations identifies food waste as one of the main causes of world hunger. In this context, food-waste reduction and sustainable packaging can be considered one of the effective solutions in addressing sustainability issues such as energy extravagance, environmental pollution, and global hunger. In this lesson example students can tie food heritage in with the design of better packaging to reduce waste in the food.

A Culturally Situated and Socially Relevant Engineering Lesson Plan

The lesson plan provided in Tables 3-1 and 3-2 has been created to help students develop not only declarative knowledge (what elements should be defined and planned for Problem Framing and Project Management) but also procedural knowledge (how to analyze, define, and document each element to develop a quality problem statement and project charter). Implementation will include a sequence of three sessions involving class discussions and a team-based design project. The lesson offers a context of cultural diversity through food heritage and socially relevant problems related to food waste/sustainability, giving students an opportunity to connect to different cultures and society.

Table 3-1 Lesson Overview

LESSON PURPOSE This lesson was designed to teach students how to scope a design problem and then plan a design project for solving the problem. This lesson includes (a) students' homework and class discussions to engage them in a culturally situated context (food heritage) and a socially relevant problem (food waste/sustainability) and (b) an experiential, team-based activity to provide them with in-depth opportunities to learn and apply two fundamental concepts of engineering design (*Problem Scoping and Project Management*).
ENGINEERING CORE & SUB-CONCEPTS • Engineering Practice - Engineering Design ▪ Problem Framing – Identifying Design Parameters, Problem Statement Development ◦ Student can construct justified problem statements that highlight the key elements of a design scenario, including multiple perspectives, to guide the evaluation of trade-offs between multiple, and sometimes conflicting, goals, criteria, and constraints during a design project. ▪ Project Management - Initiating and Planning ◦ Student can plan and manage a design project to achieve the desired goals within the established constraints through the application of appropriate project management strategies and techniques (e.g., team charters, Gantt charts).

LEARNING OBJECTIVES

At the end of this lesson, students will be able to

- Develop a problem statement by identifying explicit and implicit goals and constraints involved in a given design scenario and define them in their own words.
- Create a project charter by clearly addressing a problem to be solved, project scope and goals, organization, processes, action plans and schedules, and potential risks.
- Self-evaluate their problem statements and project based on an assessment rubric.

ENDURING UNDERSTANDINGS

- An engineering problem is ill-structured with multiple, often conflicting goals/constraints and can be represented and solved in many different ways.
- The success of a design project depends on various contextual factors as well as technical factors.
- As contextual factors can be changed at any time and be uncontrollable, project planning involves predicting possible changes and preparing measures for coping with the changes.

DRIVING QUESTIONS

- How can a problem situation be analyzed and structured?
- What are the essential elements of a problem statement?
- What are the perceived assumptions of a problem that unnecessarily limit design opportunities?
- What elements should be defined in planning a design project?
- How can potential changes or risks be analyzed and predicted?

SOCIALLY RELEVANT PROBLEM

In the United States food waste has gained attention because of its relationship to the world hunger problem. There have been proposed strategies to reduce food waste in the food supply chain. Sustainable packaging is considered one of the effective ways to solve the problems related to food waste. Students will be provided a design challenge asking to design a food-waste reducing, environmentally friendly container for their school cafeteria that is adding a new culturally specific food item to its lunch menu.

CULTURALLY SITUATED CONTEXT

Students will be situated in diverse cultures through food. They will explore a specific food involved in their own culture or family and introduce how to make, store, and eat it to team members who may be foreign to the food. Furthermore, they will be provided a design challenge asking to design a food-waste reducing, environmentally friendly container for their cultural food.

REQUIRED PRIOR KNOWLEDGE & SKILLS

For the lesson, students may need

- Skills to search and organize information through the Internet
- Skills to use Microsoft or Google documentation tools
- Knowledge about engineering design process

CONNECTED STEM STANDARDS

- Standards for Technological Literacy - 4, 5, 8, 9, 11, 13
- Next Generation Science Standards – MS-ETS1.1

CAREER CONNECTIONS

Students may become interested in careers related to

- Engineering: industrial engineering, environmental engineering, packaging engineering, material science, quality engineering
- Design: packaging design
- Business Management: restaurant management, market research, business consulting

The lesson plan provided in Table 3-2 includes a sequence of three sessions. In the first session, teachers engage students' interest by connecting food with different cultures and bringing sustainability problems related to food waste into a classroom discussion. Then, at the end of the session, teachers make teams and ask them to choose a food item. The teams are then expected to research food-waste reduction and environmentally friendly packaging. In the second session, teachers allow time for students to reflect and discuss their prior learning and experience with engineering design challenges, first in their teams and then as a class. Teachers can help to correct students' potential misconceptions and guide how to scope a design problem and plan a design project to solve the problem. Also, through the class discussion about criteria of successful problem scoping and project planning, teachers create a rubric with students. This activity will help students build a deeper understanding of the concepts, and the rubric can be used by the students and teachers to evaluate their work at the end of this lesson. At the end of the session, teachers provide a design challenge and ask student teams to scope a design problem and plan a design project. An example of the design challenge is described in Figure 3-3, which includes the topic of cultural cuisine and a food-waste problem. Teachers can make the example more authentic by specifying the current situation based on students' experience in their school cafeteria. Then, until the third session, each student team works on analyzing the given problem situation, scoping the problem, and developing a problem statement and a project charter (Table 3-3). During the third session, teams present their problem statements and project charters and evaluate themselves and other teams based on the rubric they created in the last session.

Table 3-2 Engineering Design-Based Lesson Plan

AIMS FOR ENGINEERING LEARNING INITIATIVES

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 postsecondary program toward an engineering-related career.

Engage: Sets the context for what the students will be learning in the lesson and captures their interest in the topic by making learning relevant to their lives and community.

[Session 1]

Providing a culturally situated context

- Before the class session, students select and research a food item from their own heritage to identify any cultural meanings and to determine how to make, store, serve, and eat the food.

- In the class session, teachers divide students into small teams with three or four members.

- In a team, students present their research on a food item to members. Then, within the team, they select a food that is most appropriate for their lunch based on its nutritional information.

Presenting a socially relevant problem

- Teachers explain the food supply chain, which is how a food product is made from raw materials and then goes to landfill or recycling. Then, teachers introduce the problem of food waste, presenting statistical data and a video.

- In their teams, students discuss why food waste matters and how it can impact humans and the environment. Then students share their team discussion with the whole class.

- During the class discussion, teachers focus on the global hunger problem, which is closely related to food waste, by addressing the United Nations Zero Hunger Challenge.

- Teachers explain how and why sustainable packaging can reduce food waste. Then, teachers assign homework for teams to research into the supply chain of the team's food and innovative ideas for packaging for it.

Explore: Enables students to build upon their prior knowledge while developing new understandings related to the topic through student-centered explorations.

[Session 2]

Reflecting on prior knowledge of and experience in engineering design

- Teachers ask students to reflect on engineering design processes, engineering design problems, and design requirements or constraints.

- In their teams, students share their thoughts based on prior learning and experience in engineering design.

Exploring the concepts of problem framing and project planning

- Teachers ask the student teams to develop a concept map describing what elements should be analyzed and defined when planning to solve a design challenge, how each element can be related to one another, and how each element can influence the success of a project to solve the design challenge.

- Each team presents the concept map to the whole class. Teachers give feedback on it so that students can address and accurate their misunderstandings by themselves.

- Review the Performance Expectation for Problem Framing in Appendix A.

Explain: Summarizes new and prior knowledge while addressing any misconceptions the students may hold.

Explaining problem framing and project planning with a project charter

- Teachers introduce a project charter for scoping and planning a design project, explaining its purpose, main uses, and elements (e.g. problem statement, goals, scope, deliverables, risks and issues, assumptions or dependencies, process and timeline, budget and resources, team organization, potential stakeholders, etc.). The explanation should include why each element is important, how it relates to one another, what should be researched and analyzed to define it, what decisions should be made for it, and how to document it within the charter.

- Teachers can also introduce S.M.A.R.T. criteria or a Gantt chart that are used in project planning and management.

- A sample Project Charter Template is provided in **Table 3-3.**

Developing an assessment rubric with students

- Teachers lead a class discussion about effective problem statement development and project planning. Students can share their thoughts on criteria for each element of a project charter.

- Teachers can provide feedback to improve students' understanding. Based on the discussion, teachers develop a project planning assessment rubric with students.

Engineer: Requires students to apply their engineering knowledge and practices, as well as their engineering habits of mind, to define a problem and develop, make, evaluate, and refine a viable solution.

Requiring students to apply their learning through planning a project

- Teachers provide a design challenge asking them to design a food-waste reducing, environmentally-friendly packaging for their food that will be served in the school cafeteria. See **Figure 3-3.**

- Teachers offer a project charter template and ask them to scope a design problem and then plan a project to solve the problem.

[Session 3]

- Student teams work on their project charters, using the template in **Table 3-3** and referring to the assessment rubric. Students may need to perform additional research about their food items and packaging technologies, interview cafeteria managers, staffs, teachers, and their classmates, or explore other local restaurants' packaging strategies.

- For facilitating students' collaboration and allowing them to get teachers' feedback during working on it, teachers require students to use Google Docs (or an acceptable cloud sharing tool).

Evaluate: Allows students to evaluate their own learning and skill development in a manner that empowers them to take the necessary steps to master the lesson content and concepts.

- Each team evaluates their own project charter based on the rubric they developed at the last class session.

- Student teams present their project charters to the whole class. During presentations, students evaluate other teams' project charters based on the rubric.

Note. Lesson format adapted from Grubbs & Strimel (2015).

Figure 3-3. Design Challenge

DESIGN CHALLENGE

The school cafeteria is planning to add a new item to its lunch menu. The cafeteria's manager wanted to highlight a cultural food product from the school community. Last semester, parents, teachers, and students, including your team, proposed various food product ideas. Today the cafeteria manager decides to add your team's food item to the lunch menu, aiming at launching it next semester. Also, the manager asks your team to design a food-waste reducing, environmentally friendly packaging for the food.

Table 3-3 Project Charter Template

<table>
<tr><td colspan="5">Project Title</td></tr>
<tr><td colspan="2">Problem Statement</td><td colspan="3">Goal Statement</td></tr>
<tr><td colspan="2">Project Scope</td><td colspan="3">Deliverables</td></tr>
<tr><td colspan="2">Potential Risks & Plans</td><td colspan="3">Assumption/Constraints</td></tr>
<tr><td colspan="2">Team Organization</td><td colspan="3">Project Milestone</td></tr>
<tr><td>Name</td><td>Role & Responsibilities</td><td>Phase</td><td>Output</td><td>Target Date</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Estimated Budget and Resources</td><td colspan="3">Stakeholders</td></tr>
</table>

Summary

Chapter 3 provided details and examples for helping to ensure that the content of this framework is implemented through the lens of equity, diversity, and inclusion. It is the authors' hope that these values will be integrated into the processes of content development, knowledge construction, unconscious bias elimination, pedagogical practice, and school culture. Additionally, they hope that the examples can help to model these values and aid in truly achieving engineering literacy for all children. In doing so, engineering learning can aim to close the equity gaps for student groups that have been historically or systemically underserved. As highlighted by Martin (2011), it is crucial that these types of efforts are expanded to provide quality engineering learning experiences for all students, in an effort to meet the increasing demand for a diverse engineering workforce, especially including Black engineers. While the approaches outlined in this chapter can support educators in developing a mindset toward creating engineering learning experiences that reach more students, building a culture of engineering learning that represents, values, and celebrates different perspectives and serves the whole of society requires long-term commitments from all educational stakeholders. However, the framework aims to provide a unifying vision to guide P-12 engineering education from being a subject for the fortunate few to an opportunity for all. This comes at a time when our nation requires those who are proficient in the concepts and practices of engineering more than ever.

Chapter IV

Looking Forward

P-12 engineering education is a still emerging trend. The types of learning articulated in this document are meant to serve as a catalyst for advancing excellence in P-12 engineering education. Teachers, researchers, and those concerned with high-quality engineering education for all should take the work presented here and seek to implement, support, challenge, and further engineering learning in ways that are valued by the communities they serve. A P-12 engineering education advancement effort should consider the types of engineering learning proposed in this document as well as in associated STEM standards (e.g., NGSS, STL, Common Core State Standards – Mathematics, K-12 Computer Science Standards). From an educational research perspective, there are a number of challenges prohibiting the proliferation of engineering programs. Chief among the research challenges facing this framework is the lack of empirical evidence of (1) student learning with concern to engineering, (2) effectiveness of implementation efforts, and (3) successful teacher professional development (both in-service and pre-service). In the following sections, we will create and describe an abbreviated list of efforts needed to bring this framework to its full potential. Some of these efforts will need to be acted upon immediately and led by groups such as AE[3] (implementation guides), while other efforts may take years and be carried out by additional research groups, schools, and associations concerned with the future of engineering learning.

Associated Grade-Band-Specific Implementation Guides

This framework posits that *Engineering Literacy* should be developed across the span of the P-12 years, scaffolding from more explicitly developing *Engineering Habits of Mind* at the early grades and moving toward more explicitly developing *Engineering Knowledge* at the higher grades, all while developing competence in *Engineering Practice* (see Chapter 1, Figure 5). In order to appropriately provide teachers, administrators, and curriculum developers with the resources to successfully implement this vision, a series of associated grade-band- specific guides will be developed. These guides will include, for each grade-band (early childhood, elementary, middle, and high), an overview of the current engineering programs, evidence of student learning with concern to engineering, sub-concepts to progress learning in engineering practices, suggested auxiliary engineering knowledge concepts and sub-concepts, proposed engineering literacy performance expectations (see Appendix A for HS example), and socially relevant and culturally situated example activities (see Chapter 3 for HS example). To support student progression toward the proposed engineering literacy performance expectations, the implementation guides will contain a comprehensive set of Engineering Performance Matrices (EPM). These dynamic guides will be developed in a similar process as described by Strimel and colleagues (2020), will seek to leverage individuals and institutions with specific grade-band expertise, and are expected to be revised intermittently as more evidence and best practices are generated over time.

An Engineering Performance Matrix is a conceptual model (adapted from Strimel et al., 2020) to demonstrate ways in which the content identified in the framework can be used to guide engineering instruction and serve as an assessment blueprint for the development of engineering literacy and competence. EPMs are intended to provide teachers with a sharper understanding of how sub-concepts may be related and how they may build upon each 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 EPM template in Figure 4-1 was developed based on relevant literature (Corcoran, Mosher, and Rogat, 2009; Duncan and Hmelo-Silver, 2009; Lehrer and Schauble, 2015; Magana, 2017), and then, following the consultation with a variety of engineering education experts, including teachers, professors, and industrial practitioners, a sample EPM was created. A sample EPM for the high school concept of Problem Framing is provided in Figure 4-2. The additional EPMs are linked for each high school concept in Appendix A. While these sample EPMs can indicate how to scaffold progress across different depths of student understanding from basic to advanced, learning must be shaped according to the individualities of students and their communities. Therefore, the hope is that this initial development will spur the refinement and expansion of the EPMs provided.

Figure 4-1. Engineering Performance Matrix (EPM) template. (Adapted from Strimel et al., 2020)

Engineering Dimension: *(Knowledge or Practice)*

Engineering Practice or Domain: *(Identified in the framework)*

Concept: *(Identified in the associated grade-band-specific implementation guides)*

Overview: *Definition and importance to Engineering Literacy. Why does knowledge of this concept matter for students?*

Level				
Level 4	I can successfully (Engineering Habit) (Engineering Context) through application of (Concept). **(Performance Task)** Performance Task: Indicator of mastery understanding by applying core-concept knowledge through engineering skill sets and habits of mind.			
	Sub-Concept #1	**Sub-Concept #1**	**Sub-Concept #1**	**Sub-Concept #1**
Level 3	I can... **(Advanced)** 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.	I can... **(Advanced)** 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.	I can... **(Advanced)** 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.	I can... **(Advanced)** 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.
Level 2	I can... **(Proficient)** Proficient Level (2): Representing solid academic performance.	I can... **(Proficient)** Proficient Level (2): Representing solid academic performance.	I can... **(Proficient)** Proficient Level (2): Representing solid academic performance.	I can... **(Proficient)** Proficient Level (2): Representing solid academic performance.
Level 1	I can... **(Basic)** Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.	I can... **(Basic)** Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.	I can... **(Basic)** Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.	I can... **(Basic)** Basic Level (1): Denoting partial mastery of prerequisite knowledge and skills that are fundamental for proficient work.

Figure 4-2. Sample Engineering Performance Matrix (EPM). (Adapted from Strimel et al., 2020)

Engineering Dimension: Engineering Practices

Engineering Practice: Engineering Design

Concept: Problem Framing

Overview: *Problem Framing* is a process that occurs early in and throughout the practice of *Engineering Design.* It 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.

Level 4	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.(Performance Task)

	Identifying Design Parameters		Problem Statement Development		Considering Alternatives
Level 3	I can evaluate the relationships between design criteria and constraints and prioritize them within a specific context of design in order to effectively balance trade-offs between any confliction goals.(Advanced)	**Level 3**	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. (Advanced)	**Level 3**	I can evaluate alternative problem frames/statements in an effort to select the ones that have the greatest opportunity to generate innovative solutions. (Advanced)
Level 2	I can infer design criteria and constraints that are not explicitly described in a provided description of a design situation. (Proficient)	**Level 2**	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. (Proficient)	**Level 2**	I can rephrase a problem from multiple perspectives to generate alternative problem frames/statements that remove assumptions limiting solution designs. (Proficient)
Level 1	I can analyze a provided description of a design situation to identify explicit design criteria and constraints. (Basic)	**Level 1**	I can identify the key elements of a design situation, including "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." (Basic)	**Level 1**	I can identify the assumptions or perceived rules associated with a problem statement that are limitations for solution opportunities. (Basic)

Supporting and Enhancing Associated STEM Standards

The *Framework for P-12 Engineering Learning* should be used to inform, compliment, and interact with other curricular frameworks and standards developed in associated STEM fields such as science education, mathematics education, computer science education, career and technical education, and technology education. It is important to highlight a few of the more obvious connections to such fields and the potential enhancements that this framework can offer to administrators, teachers, curriculum and assessment developers, and teacher preparation/professional development providers when it comes to engineering learning.

Engineering Habits of Mind

The *Framework for P-12 Engineering Learning* should support those interested in embedding Engineering Habits of Mind across the grades to orient learners to an engineering way of thinking and influence their reaction to everyday challenges. While there have been calls for the explicit fostering of useful habits in P-12 classrooms, it is uncommon for STEM education standards to include engineering habits of mind as essential components of student learning. This framework presents six habitual ways of thinking (optimism, creativity, systems thinking, collaboration, persistence, and conscientiousness), defined by the National Academy of Engineering (2019), to integrate throughout educational experiences. As habit formation is a gradual and incremental process, the framework recommends that, rather than providing specific learning instances, students should be afforded ongoing and repetitive opportunities to develop and reinforce these *Engineering Habits of Mind* within real-life contexts that are both personally and socially-relevant. These habits should be embraced by STEM education standards as essential components of engineering learning, and thus, affording teachers the opportunity to intentionally include instructional materials supporting the development of these important ways of thinking. Appropriately, these habits of mind should then be integrated within early learning environments and extend throughout a student's schooling. For example, at the elementary level, these habits could augment science learning, which has a dedicated space within a school's curriculum, and then advance in the higher grades to expand beyond the scope of science. By doing so, this approach can influence the way in which students view the world and respond to the problems they encounter as well as support them in acquiring/applying the knowledge and practices necessary resolve these problems.

Engineering Practices

The *Framework for P-12 Engineering Learning* should support those interested in a more comprehensive set of Engineering Practices and those that welcome the identification of core concepts and sub-concepts to direct and scaffold the learning of such practices. While science, technology, and computer science standards and frameworks all highlight the importance of learning about, as well as learning through, the practice of design and situate designing as the core practice of engineering, there is more to the engineering discipline. This framework intentionally identifies *Engineering Practices* that extend beyond Engineering Design to also include Quantitative Analysis, Professionalism, and Material Processing. These additional practices can help provide a more comprehensive view to adequately create and implement learning experiences that are authentic to engineering. Therefore, the *Framework for P-12 Engineering Learning* should support other STEM standards and frameworks in defining a more complete set of *Engineering Practices.* Furthermore, this framework draws attention to the core conceptual knowledge related to each of the *Engineering Practices.* These core concepts are provided to support teaching and learning approaches that seek to advance student competency in *Engineering Practice.* Few STEM education standards include engineering-related practices and those that are inclusive, for example science education, do not include the accompanying core concepts, and sub-concepts, that can be used to support performing these practices well and with increases in sophistication over time. For example, the practice of Engineering Design is described in this framework as a variety of methods and techniques that require knowledge of core concepts, such as problem framing, information gathering, decision-making, ideation, project management, design methods, and prototyping, to competently enact this practice. As depicted in Figure 4-2, these Engineering Design concepts, and the related sub-concepts, should be used to provide a sharper understanding of how to scaffold progress across different depths of student knowledge, from basic to advanced, and influence more immediate and purposeful instructional practice. Accordingly, the framework should support other fields in providing depth in engineering learning experiences while scaffolding toward more authentic and informed engineering practice.

Engineering Knowledge: Concepts in Engineering Science, Mathematics, and Technical Applications

Those concerned with STEM learning should use the *Framework for P-12 Engineering Learning* as a starting point to identify concepts relevant to engineering and organize STEM education programs. A strong understanding of mathematical, scientific, and technical concepts is essential to solve engineering problems. But, as discussed by the National Academies of Sciences, Engineering, and Medicine (NASEM), before the publication of this framework, educators had "very few places to turn for guidance on what science and mathematics concepts are most relevant to K–12 engineering education" (2020, p. 143). However, this framework now identifies *Engineering Knowledge* concepts in the domains of Engineering Science, Engineering Mathematics, and Engineering Technical Applications that are necessary to (1) help students solve problems in a manner that is analytical, predictive, repeatable, and practical, (2) situate learning in real engineering contexts, and (3) guide the development of engineering and/or integrated STEM programs. Therefore, the *Framework for P-12 Engineering Learning* is well positioned to support standards and learning objectives of associated STEM education fields as the identified domain-specific concepts can further integrate engineering learning across school subjects, add depth to engineering instruction, and assist in improving students' academic and technical achievement.

Instructional Guidance to Fit Local Needs

The *Framework for P-12 Engineering Learning* should support those looking for instructional guidance for implementing authentic and equitable engineering learning experiences to fit the needs of their communities. This framework can be positioned to support educators in adding depth, authenticity, and continuity to their engineering learning initiatives by defining and structuring instructional content that is true to engineering and coherently tied to a national perspective of the discipline. The framework can help to readily identify common engineering learning goals that all students should obtain to become engineering literate as well as the specific educational outcomes necessary to prepare them for the rigorous journey toward an engineering-related career. Rather than defining new learning expectations locally, the framework can serve as an "instructional menu" for school districts to create meaningful learning experiences for their students. By leveraging this resource, the efforts of educators can become more focused on the interests, relationships, and needs of their students. As a result, a school's engineering-related curriculum can become student and community centered as it will be better aligned with local needs while still striving to teach common habits, practices, and knowledge true to engineering. In addition, educational stakeholders can leverage the six *Guiding Principles for Engineering Programs* which includes (1) keeping equity at the forefront, (2) striving for authenticity to engineering, (3) focusing on depth over breadth, (4) building upon children's natural problem-solving abilities, (5) leveraging making as a form of active learning, and (6) connecting with student interests, culture, and experiences, to further shape equitable and substantial engineering learning experiences. Chapter 3 and Appendix B of this framework also include teaching resources associated to these guiding principles as well as examples of embedding engineering learning within instructional activities that offer opportunities for children to exercise informed engineering practices, with increased sophistication, in socially relevant and culturally situated contexts. Consequently, the *Framework for P-12 Engineering Learning* can help enhance the standards and frameworks of other STEM fields to support states, school systems, and other organizations in the development of engineering curriculum, instruction, assessment, and professional development that fits their needs.

Toward A Research Agenda for P-12 Engineering Learning

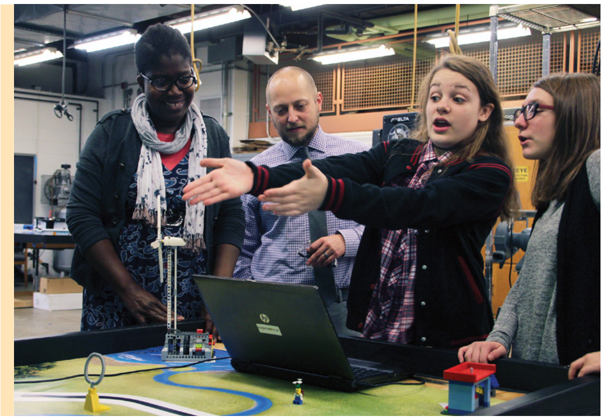
The *Framework for P-12 Engineering Learning* is intended to be a platform to promote research in P-12 engineering education. Empirical evidence is needed with concern to (1) student learning in engineering, (2) effectiveness of implementation efforts, and (3) success of teacher professional development and preparation (both in-service and pre-service). There is still much to be learned about how to best carry out the vision that will be present in the *Framework for P-12 Engineering Learning.* With so many efforts (e.g., NGSS, STEM, National Curriculum Programs) already being actualized, some of the answers may already be evident, but without a focused research agenda, impact may be minimal. For example, with concern to student learning in engineering, considerable research has been conducted by the Boston Museum of Science on their elementary curriculum program Engineering is Elementary to identify "Engineering Learning Trajectories." A research agenda for P-12 engineering learning should seek to replicate high-quality scholarship with other grade bands and curricular offerings to further the impact of the original scholarship. Furthermore, a research agenda should attend to the effectiveness of implementation efforts associated with the framework and how to best improve future efforts as more is learned about engineering learning, teacher training, school adoption and modifications, and assessments. Finally, a research agenda for P-12 engineering learning should aim to improve the capacity and quality of engineering teachers. As presented by NASEM (2020), the teaching workforce would benefit from professional development guidelines such as those created by Farmer, Klein-Gardner, and Nadelson (2014), as well as accreditation standards for pre-service teacher education programs.

Conclusion

The effort put forward in this framework is similar to those of the Engineering Concepts Curriculum Project (ECCP) carried out at the Polytechnic Institute of Brooklyn, New York, in the late 1960s. The ECCP's defining characteristic was to "work from an actual problem to the solution framework and then to the concepts" (p.2, Liao, 1970), a stark contrast to the typical science classroom of the time. The intent of this framework is to steward this belief forward. Students learn by doing. Educational research advances by examining evidence produced through students doing. In order to better understand how education takes place most successfully, we must go to the experiences of children where learning is a necessity. "Learning is a necessary incident of dealing with real situations" (p.4, Dewey and Dewey, 1915). The first step of this framework is implementation. Educators should place students in "real situations" where they engage in engineering learning. The next step of this framework would be to learn from those experiences. Educators must align, calibrate, and modify the goals presented here with the continued advancements in educational research on student engineering learning spurred forward. It is imperative that the *Framework for P-12 Engineering Learning* represent a starting point, and not a dead end for determining what all students should be able to know and do to become engineering literate.

ACHIEVING ENGINEERING LITERACY FOR ALL

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. Research suggests that increasing opportunities for all students can improve the diversity of the workforce and improve technological and innovative output.



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Appendix A

Engineering Literacy Expectations For High School Learners

For full access to the Engineering Performance Matrices visit: *www.p12engineering.org/EPM*

Engineering Habits of Mind

Engineering Habits of Mind are the traits or ways of thinking that influence how a person views the world and reacts to everyday challenges. These habits should become engrained within a student's everyday cognizance and allow them to effortlessly, efficiently, and autonomously devise solutions to problems or develop improvements to current technologies, processes, and practices (RAE, 2017). As the *Engineering Habits of Mind* are developed, they should become a student's automatic response to an engineering-related activity or problem-solving scenario that enables them to pursue a specific goal that is aimed toward a learning breakthrough or technological success (Lally & Gardner, 2013; Wood & Runger, 2016). As a goal of P-12 engineering learning, by the end of secondary school, engineering-literate students should orient themselves to an engineering way of thinking by developing the engineering habits of mind. These *Engineering Habits of Mind* include:

Engineering Habit of Mind: *Optimism (EM-OP)*
Optimism is the ability to look at the more favorable side of an event or to expect the best outcomes in various situations. It allows a person to view challenging situations as opportunities to learn and improve or as chances to develop new ideas. An optimistic habit of mind enables a person to be persistent in looking for the optimal solutions to problems. This *Engineering Habit of Mind* is important to *Engineering Literacy* because engineering-literate individuals will often experience repeated failures or unfavorable situations when solving a problem. An optimistic way of thinking provides ongoing motivation to focus on successfully resolving the problem at hand. Engineering-literate individuals, 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 (NAE, 2019). Therefore, by the end of secondary school, engineering-literate students should be able to maintain an **optimistic** outlook throughout the course of an engineering project/activity in order to persevere in accomplishing designated tasks.

Engineering Habit of Mind: *Persistence (EM-PR)*
Persistence is the ability to follow through with a course of action despite of the challenges and oppositions one may encounter. This ability also allows a person to continuously look for improvements in their operations. A persistent habit of mind enables an engineering-literate individual to develop optimal solutions to problems and see a project to its completion, as well as meet established goals and deadlines. This *Engineering Habit of Mind* is important to *Engineering Literacy,* as failure is expected, even embraced, as engineering-literate individuals work to optimize a solution to a particular challenge. Engineering, particularly engineering design, is an iterative process. It involves trying and learning and trying again (NAE, 2019). Therefore, by the end of secondary school, engineering-literate students should be able to be **persistent** throughout the course of an engineering project/activity in order to meet the project's objectives, uphold established deadlines, and be accountable for developing viable solutions to the problems they and others face.

Engineering Habit of Mind: *Collaboration (EM-CO)*
Collaboration is the ability to work with others to complete a task and achieve desired goals, which includes effective *Communication* abilities. A collaborative habit of mind enables an engineering-literate individual to connect with, and draw upon, the perspectives, knowledge, and capabilities of others to best achieve a common purpose. This *Engineering Habit of Mind* is important to *Engineering Literacy,* as most engineering projects are undertaken as a team, and successful solutions require the participation from team members with diverse backgrounds. Engineering successes are built through a willingness to work with others, listen to stakeholders, think independently, and communicate ideas collaboratively (NAE, 2019). Therefore, by the end of secondary school, engineering-literate students should be able to be **collaborative/communicative** throughout the course of a team-based engineering project/activity to leverage diverse perspectives in successfully completing designated tasks.

Engineering Habit of Mind: *Creativity (EM-CR)*
Creativity is the ability to think in a way that is different from the norm in order to develop original ideas. A creative habit of mind enables an engineering-literate individual to perceive the world in novel ways, to find unknown patterns, and make new connections between seemingly unrelated information, in an effort to develop innovative ideas or solutions to problems. This *Engineering Habit of Mind* is important to *Engineering Literacy,* as finding new ways to apply knowledge and experience is essential in engineering design and is a key ingredient of innovation. When everyone thinks exactly the same way, there can be a lack of technological and societal advancement (NAE, 2019). Therefore, by the end of secondary school, engineering-literate students should be able to be **creative** throughout the course of an engineering project/activity through the repetitive use of creativity strategies and tools to develop innovative solutions to the problems they and others face.

Engineering Habit of Mind: *Conscientiousness (EM-CS)*
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. A conscientious habit of mind enables an engineering-literate individual to maintain the highest standards of integrity, quality, ethics, and honesty when making decisions and developing solutions to ensure the public's safety, health, and welfare. This *Engineering Habit of Mind* is important to *Engineering Literacy,* as engineering has a significant ethical dimension. The technologies and methods that engineering-literate individuals 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 one's work (NAE, 2019). Therefore, by the end of secondary school, engineering-literate students should be able to be **conscientious** when making decisions throughout the course of an engineering project/activity, through repetitive questioning and critiques, to develop ethical solutions to the problems they and others face.

Engineering Habit of Mind: *Systems Thinking (EM-ST)*
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. A systems-thinking habit of mind enables engineering-literate individuals to understand how each component of a solution design or idea fits with other components while forming a complete design or idea. Additionally, it enables them to consider how a solution idea or design interacts as a part of the larger man-made and/or natural systems in which they are embedded. This Engineering Habit of Mind is important to Engineering Literacy, as 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, engineering-literate individuals need to be able to recognize and consider how all those different systems are connected (NAE, 2019). Therefore, by the end of secondary school, engineering-literate students should be able to think in terms of **systems** when making decisions throughout the course of an engineering project/activity, through recurring design critiques, in order to consider how a solution idea or design interacts with, and impacts, the world.

Engineering Practices

Engineering Practice: Engineering Design (EP-ED)

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). While this practice is often depicted as a step-by-step process, in actuality it is often a messy, iterative, and complicated practice that follows no set procedure. As such, this practice can involve a variety of methods and techniques that require a wide range of knowledge. As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be able demonstrate competence in the practice of *Engineering Design.* Competency in this practice requires knowledge of the following core concepts:

Core Concept 1: *Problem Framing (EP-ED-1)*
Problem Framing is a process that occurs early in and throughout the practice of *Engineering Design* and 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. Therefore, by the end of secondary school, engineering-literate students should be able to construct justified problem statements that highlight the key elements of a design scenario, including multiple perspectives (clients/end users), to guide the evaluation of trade-offs between multiple, and sometimes conflicting, goals, criteria, and constraints during a design project.

Core Concept 2: *Project Management (EP-ED-2)*
Project Management is the process of scoping a project and planning, organizing, and managing resources to complete the project within defined constraints (Nembhard, Yip, & Shtub, 2009). Sophistication in this process requires knowledge related to project management strategies, techniques, and tools for (a) initiating and planning project activities; (b) scoping the project and managing timelines and costs; (c) tracking and evaluating risks, quality, teams, and procurement; and (d) managing product lifecycles. This core concept is important to the practice of *Engineering Design,* as design projects are carried out within dynamic environments involving a variety of limitations. Therefore, by the end of secondary school, engineering-literate students should be able to plan and manage a design project to achieve the desired goals within the established constraints through the application of appropriate project management strategies and techniques (e.g., team charters, Gantt charts).

Core Concept 3: *Information Gathering (EP-ED-3)*
Information Gathering is the process of searching for the knowledge necessary to develop an informed resolution to a design problem. This process includes (a) identifying the specific areas to be researched/investigated, (b) collecting and synthesizing data from multiple sources, and (c) assessing the quality of the information available. This core concept is important to the practice of *Engineering Design* because once a design problem has been defined, engineering-literate individuals must decide what information they need to acquire as they work through the iterative stages of the design process to develop a design solution. Therefore, by the end of secondary school, engineering-literate students should be able to collect, evaluate, and synthesize data and knowledge from a variety of sources to inform their design process.

Core Concept 4: *Ideation (EP-ED-4)*
Ideation is the process of mentally expanding the set of possible solutions to a design problem in order to generate a large number of ideas, with the hope of finding a better and more innovative resolution. Sophistication in this process requires knowledge related to (a) divergent thinking and brainstorming techniques, (b) convergent thinking methods (including functional decomposition, which is the process breaking down the overall function of a device, system, or process into its smaller parts), and (c) employing visual-spatial abilities to convey ideas through sketching. This core concept is important to *Engineering Design,* as this practice seeks to develop creative and innovative solutions to ill-structured and open-ended problems. Therefore, by the end of secondary school, engineering-literate students should be able to generate multiple innovative ideas through both divergent and convergent thinking processes while communicating and recording ideas in two- and three-dimensional sketches using visual-spatial techniques.

Core Concept 5: *Prototyping (EP-ED-5)*
Prototyping is the process of transforming an idea into a form (physical or digital) that communicates the idea with others, with the intention to improve the idea over time through testing and the collection of feedback. Sophistication in this process requires knowledge related to (a) computer-aided design and manufacturing; (b) material selection for low-, mid-, and high-fidelity prototypes; (c) manufacturing processes for manipulating the materials; and (d) procedures for testing and modifying physical and digital prototypes. This core concept is important to the practice of *Engineering Design,* as it allows engineering-literate individuals to communicate, test, and optimize their design solutions. Therefore, by the end of secondary school, engineering-literate students should be able to build a prototype of an idea using the appropriate tools and materials for the desired prototype fidelity level while establishing the appropriate testing/data collection procedures to improve their design.

Core Concept 6: *Decision-Making (EP-ED-6)*

Decision-Making is the process of making a logical choice from a variety of options through the gathering of information and assessment of alternatives. Within the practice of *Engineering Design, Decision-Making* includes (a) making evidence/data/logic-driven decisions, (b) the application of Engineering Knowledge for justifying a design decision, (c) balancing trade-offs between conflicting design criteria and constraints, (d) using decision-making tools, such as a decision matrix, and (e) functioning within a group setting to make team-based decisions. This core concept is important to the practice of *Engineering Design,* as engineering-literate individuals are decision-makers. They make multiple decisions throughout the design process that impact the outcome of the process which can have variety of consequences to themselves, their employers, society, public health, and the environment. Therefore, by the end of secondary school, engineering-literate students should be able to make informed (data/evidence/logic-driven) choices within a design scenario through the application of *Engineering Knowledge* and the use of decision-making tools to converge on one decision within a team-setting.

Core Concept 7: *Design Methods (EP-ED-7)*

Design Methods are the processes that people apply to devise novel solutions to a broad range of problem scenarios that have an identified goal and one or more reasonable pathways toward resolution. This core concept includes knowledge related to (a) iterative design cycles, (b) user-centered design, (c) systems design, (d) reverse engineering, and (e) troubleshooting. *Design Methods* are important to the practice of *Engineering Design* because engineering-literate individuals take a more disciplined, informed, and organized approach to solve problems rather than general trial-and-error tactics. This makes it important to know and understand what design methodologies are available and how to use them. Therefore, by the end of secondary school, engineering-literate students should be able to develop a plan to manage an engineering project through the appropriate application of a specified design strategy.

Core Concept 8: *Engineering Graphics (EP-ED-8)*

Engineering Graphics are detailed and well-annotated visual illustrations that communicate the features and functions of a design or idea. Oftentimes these representations are initially created by hand, but they are almost always transferred to a digital format using three-dimensional, computer-aided design software and following a specific set of rules and guidelines. Sophistication in this process requires knowledge related to (a) the conventions for creating and reading engineering drawings, (b) dimensioning and tolerances, (c) two-dimensional sketching and computer-aided design, and (d) three-dimensional parametric modeling. This core concept is important to the practice of *Engineering Design,* as engineering-literate individuals embody, communicate, and record their ideas through graphical representations that accurately detail and convey the features and performance expectations of their designs. Therefore, by the end of secondary school, engineering-literate students should be able to interpret, analyze, and create graphical representations of a design idea following commonly accepted conventions.

Core Concept 9: *Design Communication (EP-ED-9)*
Design Communication is the process of effectively and efficiently sharing ideas, decisions, information, and results with team members and various stakeholders throughout the design process, as well as with the intended audiences at the conclusion of a design project (which can include conveying the information necessary to describe the results of the project, produce/implement a design solution, and to use the design product). Sophistication in this process requires knowledge related to (a) technical writing, (b) presentation delivery methods and tools, (c) informational graphics, and (d) visual design. This core concept is important to the practice of *Engineering Design* because an engineering-literate individual's work is only as good as their ability to communicate it to others. Therefore, by the end of secondary school, engineering-literate students should be able to articulate their ideas, decisions, and information throughout and at the conclusion of a design project, with the consideration of the target audience through a variety of verbal and visual communication strategies and tools.

Engineering Practice: Material Processing (EP-MP)

Material Processing is the practice that engineering-literate individuals use to convert materials into products, often referred to as *making.* 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. As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be able demonstrate competence in the practice of *Materials Processing Competency* in this practice requires knowledge of the following core concepts:

Core Concept 1: *Manufacturing (EP-MP-1)*
Manufacturing is the process of using technology to transform resources into valuable products. This core concept includes knowledge related to (a) design for manufacturability, (b) additive manufacturing processes, and (c) subtractive manufacturing methods. This core concept is important to the practice of *Material Processing* because the design of products is affected by factors that are specific to the ability to effectually manufacture the product itself. Accordingly, engineering-literate individuals are required to apply the appropriate knowledge, processes, tools, and equipment for developing effective and efficient processes for producing quality products. Therefore, by the end of secondary school, engineering-literate students should be able to design a product in such a way that it is easy to produce and then make the product by applying appropriate manufacturing processes.

Core Concept 2: *Measurement & Precision (EP-MP-2)*
Measurement is the process of comparing the qualities of an object, such as size, shape, or volume, to an established standard in order to describe, analyze, or plan to modify the object. ***Precision*** in measurement includes the determination of the tolerances and dimensional controls necessary for the quality production of products. Accordingly, this core concept includes knowledge related to the appropriate application of (a) measurement tools and instruments (including linear, diameter, and angle measuring devices, as well as indirect-reading/automated instruments), (b) performing precise measurements for the accurate layout of a production process, and (c) ensuring accuracy through appropriate unit analysis and engineering notation. This core concept is important to the practice of *Material Processing* because engineering-literate individuals are required to apply appropriate measurement practices and tools in the design, fabrication, and communication of technological products and systems. Also, as measurements are provided in many different forms and inaccuracy in measurement calculations can cause major problems, engineering professionals need the mathematical skills to conduct unit conversions or analyses. Therefore, by the end of secondary school, engineering-literate students should be able to select the appropriate measurement devices and units and apply them with precision to design, produce, and evaluate quality products.

Core Concept 3: *Fabrication (EP-MP-3)*
Fabrication is the process of making a product or the parts of a product to be assembled into a final product. Sophistication in this process requires knowledge related to (a) tool selection, (b) product assembly, (c) hand tools, (d) equipment and machine tools, and (e) quality and reliability. This core concept is important to the practice of *Material Processing,* as engineering-literate individuals are required to use appropriate processes, tools, and equipment to produce technological products and systems that are of reliable quality. Therefore, by the end of secondary school, engineering-literate students should be able to choose the appropriate tools, processes, techniques, equipment, and/or machinery to make a quality and reliable product/system, based on a plan or workable approach, that meets the specified design criteria of a customer in accordance with engineering standards.

Core Concept 4: *Material Classification (EP-MP-4)*
Material Classification is the process of cataloging solid materials, according to their atomic and molecular characteristics and properties, to aid in the selection of a suitable material for a particular application, as well as the processes necessary for manipulating the materials in a suitable manner. This core concept includes knowledge related to the micro- and macrostructures of the four main divisions of the material class system which are (a) metals/alloys, (b) polymers, (c) ceramics, and (d) composites. *Material Classification* is important to the practice of *Material Processing* because engineering-literate individuals must consider material properties in order to make informed decisions when selecting and applying the most appropriate materials for the production of technological products and systems. Material selection is based on fabrication requirements, such as the material's machinability, castability, and weldability, as well as its intended final shape, required mechanical properties, service necessities, tolerances, availability, and costs. Therefore, by the end of secondary school, engineering-literate students should be able to distinguish between different materials in terms of their structures and properties and determine how to apply the materials to design/create quality products in a suitable and safe manner.

Core Concept 5: *Casting/Molding/Forming (EP-MP-5)*
Casting and Molding are the processes that give materials shape by introducing a liquid material into a mold that has a cavity of the desired size and shape, and then allowing the material to solidify before being removed from the mold. ***Forming*** is the process of applying pressure to a material to cause it to flow into a new shape. This core concept includes knowledge related to (a) producing and implementing molds, (b) forging, (c) extruding, and (d) rolling. This core concept is important to the practice of *Material Processing,* as most metals, ceramics, and plastics can be shaped and sized to meet specified needs through the processes of casting and molding as well as forming. Engineering-literate individuals apply an understanding of these processes to inform their decisions when developing a design and actually changing the shapes of materials. Therefore, by the end of secondary school, engineering-literate students should be able to use knowledge of Casting/Molding/Forming to inform their decisions when developing a design or physically changing the shapes of materials.

Core Concept 6: *Separating/Machining (EP-MP-6)*
Separating/Machining include the processes that give an object a desired form by removing excess materials, which includes knowledge related to basic machine operations of (a) drilling, (b) cutting, (c) milling, (d) turning, (e) grinding, and (f) shearing. This core concept is important to the practice of *Material Processing,* as the related operations are the foundation for production and manufacturing of physical products. Furthermore, engineering-literate individuals apply an understanding of these processes to inform their decisions when developing a design and performing the operations to remove undesired materials to achieve a desired form of a product. Therefore, by the end of secondary school, engineering-literate students should be able to use knowledge of Separating/Machining to inform their decisions when developing a design or physically changing the shapes of objects by removing excess material.

Core Concept 7: *Joining (EP-MP-7)*
Joining is the process of creating a product from two or more parts through the actions of bonding and/or mechanical fastening. This core concept includes knowledge related to the basic methods of (a) fastening with both mechanical fasteners and mechanical force, (b) adhesive bonding, (c) flow bonding (brazing and soldering), and (d) welding. *Joining* is important to the practice of *Material Processing,* as very few products are made from just one part. Furthermore, engineering-literate individuals apply an understanding of these joining processes to inform their decisions when developing a design and performing the operations to assemble a product from multiple parts. Therefore, by the end of secondary school, engineering-literate students should be able to use knowledge of joining methods to inform their decisions when developing a design or physically assembling parts into a quality product.

Core Concept 8: *Conditioning/Finishing (EP-MP-8)*
Conditioning is the process of changing the internal structure of a material to adjust the material's properties to better meet desired criteria. ***Finishing,*** on the other hand, is the process of beautifying and extending the life of a product by establishing a protective coating on the object. This core concept includes knowledge related to the basic methods of (a) conditioning internal structures, (b) polishing & burnishing, (c) surface coat finishing and (c) conversion finishing. *Conditioning/Finishing* is important to the practice of *Material Processing,* as materials can be conditioned to enhance their properties in order to better achieve desired results, changed to enhance their attractiveness, and protected to increase their durability. Furthermore, engineering-literate individuals apply an understanding of these processes to inform their decisions when developing a design and performing the related operations to enhance a material's properties, improve a product's appearance, and increase the product's durability. Therefore, by the end of secondary school, engineering-literate students should be able to use knowledge of conditioning and finishing methods to inform their decisions when developing a design or physically producing a quality end product.

Core Concept 9: *Safety (EP-MP-9)*
Safety is the process of reducing the chance of injury or harm through thoughtful action and, in engineering settings, includes knowledge related to (a) laboratory guidelines and standards, (b) machine and tool safety, and (c) personal protective equipment and attire. This core concept is important to the practice of ***Material Processing*** because life is full of many hazards, which can be particularly true in engineering-related environments or facilities where machines and materials are being used by people. Furthermore, engineering-literate individuals apply an understanding of safety principles and guidelines to inform their decisions when developing a design and performing the related operations toward improving their work environment. Therefore, by the end of secondary school, engineering-literate students should be able to safely, responsibly, and efficiently process materials within a working environment without causing of harm or injury to themselves or others.

Engineering Practice: Quantitative Analysis (EP-QA)

Quantitative Analysis is the practice that engineering-literate individuals use to support, accelerate, and optimize the resolution of 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 that inform predictive decision-making. As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be able demonstrate competence in the practice of *Quantitative Analysis.* Competency in this practice requires knowledge of the following core concepts:

Core Concept 1: *Computational Thinking (EP-QA-1)*
Computational Thinking is the process of dissecting complex problems in a manner that generates solutions that are then expressed as a series of computational steps that a computer can perform (Aho, 2012). Typically, this process is separated into four elements: (a) decomposition (the method of dissecting a problem into smaller more manageable tasks), (b) pattern recognition (the method of searching for similarities within problems or solutions), (c) abstraction (the method of synthesizing important information and filtering out irrelevant data while generating a solution), and (d) algorithm design (the method of creating a step-by-step solution to be carried out by a computer program) (BBC, 2018). *Computational Thinking* also includes knowledge related to (a) the formation of algorithms (including flowcharting), (b) the translation of algorithms using appropriate programming languages, and (c) software design, implementation, and testing. *Computational Thinking* is important to the practice of Quantitative Analysis, as engineering-literate individuals systematically analyze and develop algorithms and programs to develop or optimize solutions to design problems. Furthermore, computational thinking is necessary to develop efficient and automated physical systems as well as visualizations of design concepts and computational scientific models (NRC, 2012). Therefore, by the end of secondary school, engineering-literate students should be able to design, develop, implement, and evaluate algorithms/programs that are used to visualize/control physical systems that address an engineering problem/task.

Core Concept 2: *Computational Tools (EP-QA-2)*
Computational Tools are the programs, languages, and computer applications that facilitate engineering tasks, including (a) spreadsheet tools (e.g., Microsoft Excel), (b) system design tools (e.g., LabView), and (c) computational environments (e.g., MATLAB). *Computational Tools* are important to the practice of *Quantitative Analysis,* as mathematical modeling is an integral part of the engineering design process. Engineering-literate individuals use such tools to facilitate the tasks of computing complex equations, managing large amounts of data, developing programs to process/analyze quantitative data, and communicating information. Furthermore, these tools enable users to design digital prototypes of solutions and perform statistical calculations to determine how well a solution will perform as well as why a solution performed in the way that it did. Therefore, by the end of secondary school, engineering-literate students should be able to select and use the appropriate computational tools to analyze quantitative data related to an engineering problem and to communicate/predict the effectiveness of a solution design.

Core Concept 3: Data Collection, Analysis, & Communication (EP-QA-3)
Data Collection, Analysis, & Communication are the processes of gathering, recording, organizing, examining, interpreting, and sharing data from a variety of sources, such as experiments, design calculations, economic analyses, and statistical procedures, throughout an engineering project. Sophistication in these processes requires knowledge related to (a) data collection techniques, (b) using data to inform decisions, (c) data visualization, (d) estimation, and (e) appropriately reporting data to the designated audience. *Data Collection, Analysis, & Communication* are important to the practice of *Quantitative Analysis,* as engineering-literate individuals collect, organize, and analyze quantitative data to understand and solve a problem as well as regularly communicate information about the results of their work with their clients and invested stakeholders. Therefore, by the end of secondary school, engineering-literate students should be able to select and implement the most appropriate methods to collect and analyze quantitative data and then make, justify, and share a conclusion based on the analysis.

Core Concept 4: *System Analytics (EP-QA-4)*
System Analytics is the process of investigating systems and calculating the way in which a system's components interact with each other, how they function over time, and the way in which they operate within the context of larger technological and natural systems. A system can be described as any entity or object that consists of parts, each of which has a relationship with all other parts and to the entity as a whole. These parts work together in a predictable or planned way to achieve a specific goal. *System Analytics* requires knowledge related to (a) system inputs (e.g., people, materials, tools/machines, energy, information, finances, and time), (b) system processes (e.g., design, production, management), (c) system outputs (including desirable, undesirable, intended, unintended, immediate, and delayed outputs), (d) system feedback and control (including both internal and external controls), and (e) system optimization. This core concept is important to the practice of *Quantitative Analysis,* as every physical and digital system is intertwined with a variety of natural, social, and technological systems, and are themselves systems developed through a system. The ability to analyze the design, function, and interaction of systems enables the development of dynamic controls that use data-comparing devices and sensors to optimize and automate system operations. Therefore, by the end of secondary school, engineering-literate students should be able to analyze an engineering system by identifying its inputs, outputs, processes, and feedback loops and implement controls to predict and optimize system performance.

Core Concept 5: *Modeling & Simulation (EP-QA-5)*
Modeling & Simulation is the process of using a variety of media, both physical and digital, to determine how well a design idea will perform and to communicate a design idea to others. Sophistication in this process requires knowledge related to (a) creating scaled physical models, (b) developing computational simulations, (c) establishing mathematical models, (d) collecting data through destructive testing and failure analysis, and (e) design validation through calculations. This core concept is important to the practice of *Quantitative Analysis,* as modeling and simulating actual events, products, structures, or conditions through mathematical, physical, and graphical/computer models helps engineering-literate individuals to predict the effectiveness of their solutions prior to producing a high-fidelity prototype, which can save valuable resources (time, materials, money, etc.). Therefore, by the end of secondary school, engineering-literate students should be able to develop and use a variety of models to simulate, evaluate, improve, and validate design ideas.

Engineering Practice: Professionalism (EP-P)

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. As a goal of P-12 Engineering Learning, by the end of secondary school, engineering-literate students should be able demonstrate competence in the practice of *Professionalism.* Competency in this practice requires knowledge of the following core concepts:

Core Concept 1: *Professional Ethics (EP-P-1)*
Professional Ethics are the principles of conduct that govern the actions of an individual or group. In engineering, ethics enable engineering professionals to make the best choices and do the "right" thing even when no one is looking. This core concept includes knowledge related to (a) the morals, values, & ethics continuum, (b) the engineering code of ethics, and (c) legal and ethical considerations. *Professional Ethics* is important to *Professionalism,* as engineering-literate individuals are expected to maintain the highest standards of integrity and honesty when making decisions. These decisions, and the resulting design solutions, must be ethical to protect the public's safety, health, and welfare. However, knowing what is the "right thing" can sometimes be difficult, and it often involves making choices between conflicting alternatives. Therefore, by the end of secondary school, engineering-literate students should be able to personally interpret the engineering code of ethics in an effort to make ethical decisions while engaged in an engineering project.

Core Concept 2: *Workplace Behavior/Operations (EP-P-2)*
Workplace Behavior/Operations are the actions and activities of managing the internal functions of the business or organization in which one operates, following the appropriate rules of conduct and ethical guidelines, so that the entity runs as efficiently and honorably as possible. This core concept includes knowledge related to (a) ethical guidelines for public health, safety, and welfare, (b) responsible conduct of research, (c) maintaining a professional workplace culture, (d) ethical business operations, (e) creating and honoring agreements/contracts, (f) professional liability, and (g) public policy and regulations. *Workplace Behavior/Operations* is important to *Professionalism,* as engineering-literate individuals are required to observe the ethical standards for performing their services, including developing and delivering solutions to the public, communicating and cooperating with other professionals, and working for organizations and communities. Therefore, by the end of secondary school, engineering-literate students should be able to establish the appropriate work culture among team members in order to maintain honesty and integrity within an engineering project.

Core Concept 3: *Honoring Intellectual Property (EP-P-3)*

Honoring Intellectual Property concerns protecting one's work, and the work of others, to ensure that ideas, inventions, or innovations are not stolen, used without permission, or claimed as another's work, in order to uphold professional integrity in the creative pursuit that is engineering and design. This core concept includes knowledge related to (a) intellectual property terminology and regulations, (b) patents, copyright, and licensure, and (c) referencing sources and plagiarism. This core concept is important to *Professionalism,* as engineering-literate individuals must honor and leverage the value of others' creations and innovations and protect their own intellectual property while ensuring that the highest standards of quality and integrity are upheld when solving problems. In this area, students should learn about a variety of intellectual properties and the process of accessing or applying for the intellectual properties. Therefore, by the end of secondary school, engineering-literate students should be able to leverage the work of others, while protecting their own, following the appropriate ethical conventions related to intellectual property.

Core Concept 4: *Technological Impacts (EP-P-4)*

Technological Impacts are the effects, both positive and negative, that result from developing and using technologies. It is impossible to explore how each technological product or process will impact the future. However, it is important to understand how engineering problems and their solutions are interconnected with relevant (a) environmental, (b) global, (c) social, (d) cultural, (e) economic, (f) individual, and (g) political issues in order to evaluate/revise solutions in terms of these various nontechnical factors. This core concept is important to *Professionalism,* as engineering-literate individuals recognize that having control over Earth's future carries with it serious responsibilities, so they must consider nontechnical factors as well as technical factors when analyzing and solving problems. Therefore, by the end of secondary school, engineering-literate students should be able to analyze the potential impacts of their decisions during an engineering project, considering a variety of nontechnical concerns, to evaluate their work in respect to relevant societal issues.

Core Concept 5: *Role of Society in Technological Development (EP-P-5)*

The ***Role of Society in Technological Development*** involves humanity's input in the decisions regarding the creation and implementation of technologies, based on the predicted outcomes of its applications as well as the evaluation of its unpredicted outcomes. This core concept includes knowledge related to (a) society's needs and desires, (b) designing for sustainability, (c) cultural influences, (d) appropriate technology applications, (e) inclusion and accessibility, (f) public participation in decision-making, and (g) scaling technology. The *Role of Society in Technological Development* is important to *Professionalism,* as technology by itself is neutral and does not affect people or the environment. However, it is the way in which people develop and use technology that determines if it is helpful or harmful. As such, engineering-literate individuals must work along with communities to address their needs and develop appropriate engineering solutions. Therefore, by the end of secondary school, engineering-literate students should be able to evaluate the interactions between engineering activities and society in order to create solutions to engineering problems that consider the voice, culture, needs, and desires of the people in which the solution touches.

Core Concept 6: *Engineering-Related Careers (EP-P-6)*
Engineering-Related Careers are the wide variety of occupations that require technical knowledge to design, assess, implement, use, scale, and/or maintain technologies across industries, including, though not limited to, skilled production workers, technicians, engineering technologists, engineers, engineering managers, and engineering entrepreneurs. This core concept includes knowledge related to (a) the nuances of engineering-related career pathways and disciplines, (b) professional licensing, (c) professional/trade organizations, and (d) engineering entrepreneurship. Knowledge of *Engineering Related Careers* is important to *Professionalism,* as there are a variety of professions and employment opportunities in engineering and technology fields across industries, such as manufacturing, construction, medicine, transportation, and the military, in which one can make a difference and earn a living. Therefore, by the end of secondary school, engineering-literate students should be able to appraise engineering-related careers and the general requirements of the associated employment opportunities to create a long-term plan to pursue their career goals, whether it be engineering related or not.

Engineering Knowledge

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 engineering-literate students 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. In addition, 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. 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.*

Engineering Knowledge Domain: Engineering Sciences (EK-ES)

Engineering Science is a knowledge base consisting of the basic principles and laws of the natural world that 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, and different solution approaches may draw on students' knowledge gained from a variety of domains. In the P-12 classrooms, students should engage in experiences that position Engineering Sciences as a way to inform their engineering practice. As a goal of P-12 Engineering Learning, engineering-literate students should be able to recognize and, when appropriate, apply Engineering Science concepts to inform their engineering practice in order to solve problems in a manner that is analytical, predictive, repeatable, and practical. For example, students may be able to recognize and, when appropriate, draw upon knowledge of:

Auxiliary Concept 1: *Statics (EK-ES-1)*
Statics is a fundamental physics concept that focuses on the equilibrium of bodies that are subjected to a force system. It primarily concerns the application of Newton's laws of motion to analyze loads placed on objects at rest or at a constant velocity. Because these objects are resting or have a constant velocity, the sum of all of the forces applied to the object must be equal to zero. *Statics* is important to Engineering Literacy, as it is the basis on which engineering professionals analyze physical systems that are void of acceleration. For example, the application of statics enables the analysis of forces applied to physical objects/systems such as trusses, cables, and chains. In addition, statics enables engineering professionals to calculate the magnitudes of the components of forces applied to an object using a series of equations. Therefore, by the end of secondary school, engineering-literate students should be able to draw upon the knowledge of statics content, such as (a) *determining the resultants of force systems,* (b) *finding equivalent force systems,* (c) *conditions of equilibrium for rigid bodies,* (d) *the analysis of frames/trusses,* (e) *finding the centroid of an area,* and (f) *calculating area moments of inertia,* to analyze the forces within a static system to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 2: *Mechanics of Materials (EK-ES-2)*
Mechanics of Materials concerns the mechanical behavior of deformable bodies when they are subjected to stresses, loads, and other external forces. This concept is important to Engineering Literacy, as it is the basis on which engineers select materials and modify their forms to create mechanical devices and systems. For example, the application of this knowledge enables professionals to predict structural failure by using Stress-Strain analyses and Young's modulus to evaluate an object's deformation resulting from applied loads. Therefore, by the end of secondary school, engineering-literate students should be able to draw upon the knowledge of the *Mechanics of Materials,* such as (a) *stress types and transformations,* (b) *material characteristics,* (c) *stress-strain analysis,* (d) *material deformations,* (e) *material equations,* (f) *phase diagram,* (g) *Mohr's circle,* and (h) *Young's modulus,* to analyze the properties, compositions, and behaviors of available or needed materials to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 3: *Dynamics (EK-ES-3)*
Dynamics concerns the analysis of objects that are accelerating as a result of acting forces. This indicates that the sum of all forces acting upon the object under investigation is not equal to zero. *Dynamics* can be divided into two main areas, kinetics and kinematics. Kinetics focuses on the study of forces that cause motion, such as gravity or torque, while kinematics focuses on the study of describing motion using quantities such as time, velocity, and displacement without the concern of the forces involved. *Dynamics* is important to Engineering Literacy, as it is the basis on which engineering professionals analyze physical systems that are in motion. For example, the application of dynamics enables professionals to solve problems where the forces are not in equilibrium by relating the forces and moments acting on a body to the resulting motion. Therefore, by the end of secondary school, engineering-literate students should be able to draw upon the knowledge of *Dynamics* content, such as (a) *kinetics,* (b) *kinematics,* (c) *mass moments of inertia,* (d) *force acceleration,* (e) *impulse momentum,* and (d) *work, energy, and power,* to analyze the forces within a dynamic system to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 4: *Thermodynamics (EK-ES-4)*
Thermodynamics is the science of transferring energy from one place or form into another place or form, which includes the study of heat and temperature and the relation of these factors to work, energy, and power. This concept is important to Engineering Literacy, as it is the basis on which engineering professionals calculate and predict how forms of energy are converted into other forms, in order to create, improve, and create technological products and systems such as power plants, air-conditioning/heating units, and automobile engines. Therefore, by the end of secondary school, engineering-literate students should be able to draw upon the knowledge of *Thermodynamics* content, such as (a) *the Laws of Thermodynamics,* (b) *equilibrium,* (c) *gas properties,* (d) *power cycles and efficiency,* and (e) *heat exchangers,* to analyze the forces within an energy system to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 5: *Fluid Mechanics (EK-ES-5)*
Fluid Mechanics concerns how the laws of force and motion apply to liquids and gases. This concept is important to Engineering Literacy, as it is the knowledge that informs how engineering professionals understand, design, create, and analyze systems involving fluids such as heating and cooling equipment, pump systems, fans, turbines, pneumatic equipment, and hydraulic equipment. For example, one may use Bernoulli's equation and the conservation of mass to determine flow rates, pressure changes, minor and major head losses for viscous flows through pipes and ducts, and the effects of pumps, fans, and blowers in such systems. Therefore, by the end of secondary school, engineering-literate students should be able to draw upon the knowledge of *Fluid Mechanics* content, such as (a) *fluid properties,* (b) *lift, drag, and fluid resistance,* (c) *pumps, turbines, and compressors,* (d) *fluid statics and motion (Bernoulli's equation),* and (e) *pneumatics and hydraulics,* to analyze how fluids behave and how to measure/control their flow to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 6: *Heat Transfer (EK-ES-6)*
Heat Transfer is the scientific knowledge that builds upon the principles of thermodynamics and fluid dynamics to describe how heat moves from one body to another. For heat to transfer, a temperature difference or gradient is needed. Heat will move from a higher temperature to a lower one (hot to cold). This concept is important to Engineering Literacy, as it is the knowledge that informs how engineering professionals understand, design, create, and analyze material selections, machinery efficiency, reaction kinetics, heat exchangers, and cooling towers. Therefore, by the end of secondary school, engineering-literate students should be able to draw upon the knowledge of *Heat Transfer* content, such as (a) *conductive, convective, and radiation heating* and (b) *heat transfer coefficients,* to analyze how heat moves from one system (solid, liquid, or gas) to another in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 7: *Mass Transfer & Separation (EK-ES-7)*
Mass Transfer & Separation is the science that explains and governs a range of separation processes that include absorption, distillation, humidification and drying, and membrane separations, as well as transport processes in equilibrium. This concept is important to Engineering Literacy, as it is the basis on which engineers design equilibrium-staged chemical processes and analyze chemical or physical principles of materials in order to select appropriate techniques for mass transfer and separation operations. Therefore, by the end of secondary school, engineering-literate students should be able to draw upon the knowledge of *Mass Transfer & Separation* content, such as (a) *molecular diffusions,* (b) *separation systems,* (c) *equilibrium state methods,* (d) *humidification and drying,* (e) *continuous contact methods,* and (f) *convective mass transfer,* to analyze the mechanism of transfer due to difference in concentrations to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 8: *Chemical Reactions & Catalysis (EK-ES-8)*
Chemical Reactions & Catalysis concerns the analysis of the chemical changes that happen when two or more particles interact (chemical reactions), as well as controlling the rate at which these chemical changes occur by adding substances referred to as catalysts (catalysis). This concept is important to Engineering Literacy, as it is the knowledge that engineering professionals use to analyze and design new products and processes by controlling and using chemical reactions. For example, developing more efficient catalysts can reduce the production of environmentally harmful by-products and can enable enhanced energy-efficient production processes. More efficient catalysts can also lower the costs of producing important chemical products. Therefore, by the end of secondary school, engineering-literate students should be able to draw upon the knowledge of *Chemical Reactions & Catalysis* content, such as (a) *reaction rates, rate constants, and order,* (b) *conversion, yield, and selectivity,* (c) *chemical equilibrium and activation energy,* and (d) *fuels,* to analyze the factors influencing the processes of reaction and catalysis with mathematical models to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 9: *Circuit Theory (EK-ES-9)*
Circuit Theory is the collection of scientific knowledge used to describe the flow of electrical energy through an electrical circuit. This concept is important to Engineering Literacy, as it enables an engineering professional to mathematically represent and verify how electrical components relate to one another in order to design and develop electrical circuits to perform specific tasks appropriately. Therefore, by the end of secondary school, engineering-literate students should be able to draw upon the knowledge of *Circuit Theory* content, such as (a) *series and parallel circuits,* (b) *Ohm's Law,* (c) *Kirchhoff's Laws,* (d) *resistance, capacitance, and inductance,* (e) *wave forms,* (f) *signals,* and (g) *current, voltage, charge, energy, power, and work,* to design and mathematically justify an electrical circuit to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Engineering Knowledge Domain: Engineering Mathematics (EK-EM)

Engineering Mathematics is a knowledge base consisting of practical mathematical techniques and methods that 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 concepts in *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, and different solution approaches may draw on students' knowledge gained from a variety of domains. 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 Learning, engineering-literate students should be able to recognize and, when appropriate, apply *Engineering Mathematics* concepts to inform their engineering practice in order to solve problems in a manner that is analytical, predictive, repeatable, and practical. For example, students ***may*** be able to recognize and, when appropriate, draw upon knowledge of:

Auxiliary Concept 1: *Engineering Algebra (EK-EM-1)*

Algebra is a branch of mathematics that focuses on the conventions related to the use of letters and other general symbols, known as variables, to represent numbers and quantities without fixed values in formulas and equations. *Algebra* is important to Engineering Literacy, as engineering professionals habitually select and use algebraic content and practices in the analysis, design, and making of solutions to engineering problems. Mathematical applications are used on a daily basis to solve equations. For example, by applying Ohm's Law to an electrical circuit, a measured or known value such as the voltage can be used to determine an unknown value. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of algebraic content and practices, such as (a) *the basic laws of algebraic equations,* (b) *reasoning with equations and inequalities,* (c) *representing equations in 2D and 3D coordinate systems,* and (d) *linear algebra,* to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 2: *Engineering Geometry & Trigonometry (EK-EM-2)*

Geometry is a branch of mathematics that focuses on the measurement, properties, and relationships of points, lines, angles, surfaces, and solids. ***Trigonometry,*** which, historically, evolved from applications of geometry, specifically studies angles and angular relationships of planar and three-dimensional figures. These areas of mathematics are important to Engineering Literacy, as engineering professionals frequently select and use geometric/trigonometric content and practices in the analysis, design, and making of solutions to engineering problems. For example, related mathematical applications can help one calculate distances and angles of velocity, enable efficiency when processing materials to make a physical product, support the development of engineering graphics through computer-aided design software, and accurately create models and simulations to predict the functionality of a design idea. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of geometric/trigonometric content and practices, such as (a) *geometric measurement and dimensions,* (b) *expressing geometric properties with equations,* (c) *right triangles,* (d) *trigonometric functions,* and (e) *vector analysis,* to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 3: *Engineering Statistics & Probability (EK-EM-3)*

Statistics is a branch of mathematics that focuses on the methods of collecting, representing, collating, comparing, analyzing, and interpreting data. *Statistics* is typically combined with the study of probability theory, which involves the mathematical analysis of random phenomena to determine how likely they are to occur. These areas of mathematics are important to Engineering Literacy, as engineering professionals frequently select and use statistical content and practices in the testing, simulation, and analysis of solutions to engineering problems. For example, related mathematical applications can help one to calculate how likely an outcome of repeated experiments may be, and how a specific intervention may influence the outcome, based on the analysis of collected data. As such, engineers use statistics and probability theory to evaluate the outcome of possible solutions to engineering problems. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of statistics/probability content and practices, such as (a) *probability distributions,* (b) *descriptive statistics and measures of central tendencies (mean, median, mode),* (c) *inferential statistics and tests of significance,* and (d) *using probability to make decisions,* to evaluate/justify solutions to problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 4: *Engineering Calculus (EK-EM-4)*

Calculus is a branch of mathematics that focuses on understanding the changes between values that are related by functions of time. This involves determining how something changes, or how items add up, by breaking them into really tiny pieces. There are two different divisions of calculus: (1) differential calculus, which focuses on calculating how things change from one moment to the next by dividing it in small fragments, and (2) integral calculus, which focuses on understanding how much of something there is by piecing small fragments together. This area of mathematics is important to Engineering Literacy, as engineering professionals frequently select and use calculus content and practices in the analysis and design of solutions to engineering problems. For example, related mathematical applications can help one to accurately and efficiently calculate quantities like rates of flow of water from a tunnel or the rate of decay of a radioactive chemical. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of calculus content and practices such as (a) *derivatives,* (b) *integrals,* (c) *differential and integral equations,* and (d) *vectors, including dot and cross products,* to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Engineering Knowledge Domain: Engineering Technical Applications (EK-ET)

Engineering Technical Applications involves an interdisciplinary knowledge base consisting of the practical applications of engineering principles necessary to bring ideas to reality and to operate and carry out technical analyses of tangible engineering outputs. This knowledge, which includes auxiliary concepts of *electrical power, communication technologies, electronics, computer architecture, chemical applications, process design, mechanical design, structural analysis, transportation infrastructure, hydrologic systems, geotechnics, and environmental considerations,* relies heavily on, and is inseparable from, the application of mathematical and scientific knowledge. The *Engineering Technology* knowledge base is essential, as engineering tasks are typically open-ended and ill-defined, and different solution approaches may draw on a students' knowledge gained from a variety of domains. In the P-12 classrooms, students should engage in experiences that position *Engineering Technical Applications* as a way to inform their engineering practice. As a goal of P-12 Engineering Learning, engineering-literate students should be able to recognize and, when appropriate, apply *Engineering Technical Application* concepts to inform their engineering practice in order to solve problems in a manner that is analytical, predictive, repeatable, and practical. For example, students *may* be able to recognize and, when appropriate, draw upon knowledge of:

Auxiliary Concept 1: *Mechanical Design (EK-ET-1)*

Mechanical Design is the process of developing the mechanisms/machines necessary to convert energy into useful mechanical forms and transform resources into a desired output. This includes determining what factors influence the design of a mechanical system, how the factors relate with each other throughout the design process, and how to configure the factors to meet design criteria and constraints. This concept is important to Engineering Literacy, as it encompasses the knowledge necessary to analyze, design, and manufacture mechanical devices and systems. For example, mechanical design principles enable one to incorporate the analysis of items such as gears, shafts, fasteners, and gearboxes in terms of the fatigue and heating effects resulting from working stresses and repeated loadings in the creation of a mechanical system. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Mechanical Design* content and practices, such as (a) *machine elements/mechanisms,* (b) *manufacturing processes,* and (c) *machine control,* to forecast and validate the design performance of a mechanism or machinery component in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 2: *Structural Analysis (EK-ET-2)*

Structural Analysis concerns the process of determining the effects of loads, or forces, on physical structures, as well as their individual components, and examining what factors influence the deflection and deformation of these structural elements. This includes determining how and why structural elements may fail, break, or deform, and preventing such failures. This concept is important to Engineering Literacy, as all structures are constantly under some type of strain or stress due to a variety of forces applied to them. As such, structural analyses enable one to make informed decisions about how structures should be designed by performing the proper calculations to determine whether or not various structural members will be able to support the forces applied to them. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Structural Analysis* content and practices, such as (a) *the physical properties of construction materials,* (b) *material deflection,* (c) *material deformation,* (d) *column and beam analysis,* and (e) *the implementation of design codes,* to evaluate the structural elements of an structure design using the proper formulas and conventions necessary to calculate the effects of applied stresses or strains.

Auxiliary Concept 3: *Transportation Infrastructure (EK-ET-3)*

Transportation Infrastructure encompasses all of the interrelated physical support systems that provide the services, utilities, and commodities necessary for moving people and cargo within and between communities/countries in order for society to function proficiently. This concept is important to Engineering Literacy, as a suitable infrastructure is necessary for technological systems to function and for sustaining and enhancing a community's living conditions and economy. For example, knowledge of infrastructures enables people to design, build, and maintain appropriate transportation systems by examining factors that can influence the efficient and safe movement of people and goods and by determining how to best control these factors. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Transportation Infrastructure* content, such as (a) *street, highway, and intersection design,* (b) *transportation planning and control (including safety, capacity, and flow),* (c) *traffic design,* and (d) *pavement design,* to plan/create facilities and systems that are needed to serve a county or community while considering of a variety of criteria and constraints about the safe and efficient movement of people and goods.

Auxiliary Concept 4: *Hydrologic Systems (EK-ET-4)*

Hydrologic Systems encompass all of the interrelated physical structures and devices, as well as the natural environment (including precipitation, evaporation, streamflow, surface runoff, groundwater movement, etc.) that affect and help manage, the movement, distribution, and properties of water. This also includes knowledge of the fundamental principles of hydrology necessary to analyze and evaluate environmental conditions and determine the characteristics of hydrologic systems needed to meet design objectives. This concept is important to Engineering Literacy, as it enables one to leverage the knowledge of runoff, streamflow, soil moisture, and groundwater flow to innovate tools and methods in water distribution and collection necessary for sustaining, as well as enhancing, a community's living conditions and economy. For example, methods of data collection and error analysis associated with water in hydrology and water resources assist in the development, construction, and application of systems necessary to manage a community's water resources. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Hydrologic Systems* content and practices, such as (a) *hydrology principles,* (b) *water distribution and collection systems,* (c) *watershed analysis processes,* (d) *open channel systems,* (e) *closed channel systems (pressurized conduits),* (f) *pumping stations,* and (g) *hydrologic field tests and codes,* to analyze/model the flow of water in and out of a system, using the appropriate mathematical equations and conventions, in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 5: *Geotechnics (EK-ET-5)*
Geotechnics concerns the knowledge of the ways Earth's materials (i.e., rock and soil) behave under stresses and strains and how structures and products interact, or will interact, with their surrounding environments, as well as how the Earth's materials can be used to mitigate, prevent, or solve problems. This concept is important to Engineering Literacy, as it enables one to design the foundations of structures, plan the excavation of build sites, select the routes for roads and highways, minimize the negative impacts that structures have on the environment, and prevent the damages caused by natural hazards to make the Earth's surface more suitable for people and the development of communities. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Geotechnics* content and practices, such as (a) *geological properties and classifications,* (b) *soil characteristics,* (c) *bearing capacity,* (d) *drainage systems,* (e) *slope stability,* (f) *erosion control,* (g) *foundations and retaining walls,* and (e) *geotechnical field tests and codes,* to analyze/model the behavior of Earth's materials, using the appropriate mathematical equations and conventions, in order to solve problems in a manner that is analytical, predictive, repeatable, and practical.

Auxiliary Concept 6: *Environmental Considerations (EK-ET-6)*
Environmental Considerations focuses on managing the use of natural resources to minimize the negative impacts that human activity can have on the environment. This includes work developing new and better ways to dispose of waste and to clean up pollution while understanding the impact government regulations and the methods for analyzing environmental change. This concept is important to Engineering Literacy, as extracting natural resources and transforming them into industrial/consumer products and structures can take a major toll on the environment. For example, building a hydroelectric dam to generate electricity can alter the ecosystem for aquatic life; extraction of natural gas from subterranean rock formations could potentially contaminate water sources; and the burning of fossil fuels such as coal can contribute to increased levels of greenhouse gases in the atmosphere. As such, the knowledge relevant to *Environmental Considerations,* such as sampling and analysis techniques for surface water, groundwater, soil, and air, can aid in designing strategies to prevent/mitigate/remediate problems in an effort measurably enhance environmental quality. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Environmental Considerations* content and practices, such as (a) *ground and surface water quality,* (b) *wastewater management,* (c) *air quality,* and (d) *environmental impact regulations and tests,* in order to design methods to protect and manage our air, water, soil, and related ecosystems.

Auxiliary Concept 7: *Chemical Applications (EK-ET-7)*
Chemical Applications are the activities and knowledge related to converting materials into more usable substances as well as selecting the best materials for specific applications. This concept is important to Engineering Literacy, as engineering professionals apply their understanding of chemistry and the properties of the materials to solve a variety of problems. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Chemical Applications* content, such as (a) *inorganic chemistry,* (b) *organic chemistry,* (c) *chemical, electrical, mechanical, and physical properties,* (d) *material types and compatibilities,* (e) *corrosion,* and (f) *membrane science,* to analyze and select, or propose a novel combination of materials to produce a desired product or process.

Auxiliary Concept 8: *Process Design (EK-ET-8)*

Process Design concerns the development and organization of facilities to support the desired transformation of materials, both physically and chemically. This concept is important to Engineering Literacy, as it encompasses the knowledge necessary for coordinating the appropriate production procedures and manufacturing processes involved with transforming materials into desired end products. In addition, this knowledge supports the continual optimization of production processes and manufacturing facilities to minimize the waste of resources, enhance production efficiency, and increase an organization's profits. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Process Design* content and practices, such as (a) *process controls and systems,* (b) *process flow, piping, and instrumentation diagrams,* (c) *recycle and bypass processes,* and (d) *industrial chemical operations,* to visually represent the procedures and facilities necessary to produce a desired product.

Auxiliary Concept 9: *Electrical Power (EK-ET-9)*

Electrical Power concerns the knowledge related to the systems that generate, store, transform, distribute, and use electricity to perform work. *Electrical Power* is important to Engineering Literacy, as it enables engineering professionals to make informed decisions related to the use and creation of electrical devices and components to generate, transfer, and use electrical energy, which is critical as these decisions can greatly impact our society and environment. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Electrical Power* content, such as (a) *motors and generators,* (b) *alternating and direct current,* (c) electrical materials, (d) *electromagnetics,* (e) *voltage regulation,* (f) *electricity transmission and distribution,* and (g) *magnetism,* to determine and justify which electrical materials are most appropriate for an engineering task involving electrical power systems, using mathematical equations and the correct units.

Auxiliary Concept 10: *Communication Technologies (EK-ET-10)*

Communication Technologies are the systems and products that extend the ability to collect, analyze, store, manipulate, receive, and transmit information or data, which can include anything from graphic media to computers, cellular devices, and fiber optics. *Communication Technologies* are important to Engineering Literacy, as these systems have become intertwined with our daily lives, and in many ways society has become increasingly dependent on them. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Communication Technologies* content, such as (a) *digital communication,* (b) *telecommunication,* (c) *graphic communication,* (d) *photonics,* and (e) *network systems,* to visually represent, analyze, and propose the procedures and products necessary to effectively, efficiently, and appropriately communicate data and/or information.

Auxiliary Concept 11: *Electronics (EK-ET-11)*
Electronics are the systems and products that use small amounts of electricity for collecting, storing, retrieving, processing, and communicating data/information necessary to perform a task. This includes creating electrical circuits using both traditional analogue components as well as digital electronic components, microprocessors and microcontrollers, and programmable logic devices. This concept is important to Engineering Literacy, as engineering professionals use and apply this knowledge to design and troubleshoot the electronic devices that we use every day. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Electronics* content, such as (a) *electronic instrumentation,* (b) *electronic components (diodes, transistors, resistors, power supplies, capacitors, breadboards, etc.),* (c) *digital logic (integrated circuits, gates, flip-flops, counters, etc.),* and (d) *electrical diagrams/schematics,* to successfully choose different instrumentation, components, and materials to visually represent, analyze, design, and test an electronic device to perform a specific task.

Auxiliary Concept 12: *Computer Architecture (EK-ET-12)*
Computer Architecture concerns the knowledge related to understanding how a computer's sub-components are organized and interact with each other to perform desired functions. This includes the physical components (hardware) and operating instructions (software). The hardware comprises the computer system's central processing unit (CPU), memory, input devices, and output devices. The software includes both operating software (the programs that manage the computer's processes, memory, and operation of all other hardware and software) as well as application software (the programs that work with the operating software to perform specific tasks, such as word processing, computer aided-design, and gaming). *Computer Architecture* is important to Engineering Literacy, as computer systems are the heart of all information-processing and communication technologies, performing countless functions that have extended capabilities for calculations, automation, and communication between people and machines across the world and beyond. Therefore, by the end of secondary school, engineering-literate students may be able to, when appropriate, draw upon the knowledge of *Computer Architecture* content, such as (a) *computer hardware,* (b) *computer operating software and applications,* (c) *memory,* (d) *processors and microprocessors,* and (e) *coding,* to visually represent how the components of a computer system relate to one another and how to configure the components for desired performance.

Appendix B

Lesson Plan Template

Framework for P-12 Engineering Learning

Socially Relevant & Culturally Situated Lesson/Activity Template

Lesson/Activity Title:

Overview/Purpose:
Provide a paragraph stating the overall big idea of the lesson/activity (the what) and its intended outcome (the why).

Lesson/Activity Duration:
Provide the estimated time necessary to complete the activity.

Engineering Concepts:
Identify the intentional Engineering Practice and/or Engineering Knowledge concepts to be taught and assessed in the lesson (Found in Chapter 2 and Appendix A of the Framework).

Learning Objectives:
Provide the measurable student outcomes for lesson's concepts and performance expectations (See Framework Chapter 2 and Appendix A of the Framework).

Socially Relevant Issue/Challenge/Problem:
Describe an overarching global/local issue or challenge that is related to the Engineering Concepts (sources of inspiration can be found through the students' communities, the National Academy of Engineering's Grand Engineering Challenges, or the United Nation's Sustainability Goals).

Culturally Situated Context:
Provide a context related to the school community that connects, acknowledges, and builds upon the rich cultural backgrounds of students.

Relevant STEM Standards:
List and describe the connections between the overarching issue or challenge and relevant standards/objectives from other school subjects.

Enduring Understanding(s):
List the key takeaway items from the lesson, which transcend the lesson itself and are applicable to various situations.

Driving Question(s):
Provide questions to direct student information gathering efforts attempting to address the overarching issue or challenge, guiding them in the development their design solutions.

Career Connections:
List and describe specific career relationships that are to be incorporated throughout the lesson.

Required Student Prior Knowledge & Skills:
List and describe specific student competencies that are necessary for their success in this activity.

Engineering Design-Based Lesson Plan

LESSON/ACTIVITY SECTION	STEP-BY-STEP LESSON PLAN
Engage: Sets the context for what the students will be learning in the lesson and captures their interest in the topic by making learning relevant to their lives and community.	*Should involve an engaging activity, such as a mini-design task, to engage students in the lesson and provide the context for the lesson's overarching challenge or issue.*
Explore: Enables students to build upon their prior knowledge while developing new understandings related to the topic through student-centered explorations.	*Should include a student-centered investigation activity that will enable students to further understand the overarching challenge or issue presented in the lesson and gather information related to the topic.*
Explain: Summarizes new and prior knowledge while addressing any misconceptions the students may hold.	*Should involve a student-centered discussion of the overarching issue or challenge, as well as the student-defined problems, with the purpose of identifying and learning the key concepts necessary to begin developing potential solutions.*
Engineer: Requires students to apply their engineering knowledge and practices, as well as their engineering habits of mind, to define a problem and develop, make, evaluate, and refine a viable solution.	*Should require students to enact the engineering practices and habits, while applying the appropriate engineering concepts that are scientific, mathematical, and/or technical in order to complete the engineering tasks to resolve the challenge at hand.*
Evaluate: Allows students to evaluate their own learning and skill development in a manner that empowers them to take the necessary steps to master the lesson content and concepts.	*Should require students to reflect on the effectiveness of their processes and products to complete the engineering tasks as well as determine their level of achievement toward the intended learning objectives/outcomes.*

Assessment Tools:

Teacher Preparation:

Tools/Materials/Equipment:

Laboratory/Classroom Safety & Conduct:

Student Resources:

Teacher Resources:

Key Vocabulary:

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