# Developing a Framework for P-12 Engineering Learning

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

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# Summary

The *Framework for P-12 Engineering Learning* was developed and informed through engagement with the engineering and education communities. The development process brought together teachers, administrators, researchers, outreach coordinators, and organizations that embodied education from primary through post-secondary school, as well as industry representatives. The framework project was led by the *Advancing Excellence in P-12 Engineering Education* (AE$^3$) research collaborative under guidance from the *American Society of Engineering Education* (ASEE). A variety of other organizations played special roles during the development process, including the *Maryland High School Society of Engineering Programs* (MSHSEP), *Baltimore County Public Schools*, and *MathWorks*. As a result, the framework has been developed from over 3 years of research and development activity that has engaged over 300 P-12 engineering education stakeholders from 32 states and involved 3 multi-day symposia that served as focus groups around P-12 engineering education to provide concrete examples of best-practices from around the country.

The development timeline consisted of three phases;

- Phase 1: Research & Investigation which included literature reviews, content organization, and a Delphi Study to help set the epistemological foundation for the subject and to begin identifying “what P-12 engineering education is” and “where it should be,”
- Phase 2: Development & Testing which included a series of action-oriented symposia with teachers, researchers, administrators, and other stakeholders and pilot implementation sites to establish and validate the core components of the framework including the concepts and practices for engineering literacy,
- Phase 3: Synthesis & Writing which included the AE3 team assembling the three years of input from the engaged community into a coherent framework with feedback from ASEE representatives.

Each of these phases involved iterative cycles of research, design, and experimentation in order to gather the data necessary to develop a validated taxonomy of engineering concepts and assess the potential effectiveness of any related instructional sequences. This work has included (a) conducting the activities to identify and refine agreed upon concepts and sub-concepts for engineering knowledge and practice, (b) establishing an instructional sequence for progressions of learning in engineering, (c) coordinating focus groups for validation, (d) designing curricular examples for implementation using socially-relevant/culturally-situated learning activities, and (e) establishing pilot sites for testing and refining this work within classrooms.

It is important to note that the outcome of this process is a framework aimed toward providing (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, curriculum, instruction, assessment, and professional development that helps to better democratize engineering education across grades P-12. While the framework 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 and a roadmap or progression of learning toward these endpoints. However, a logical next step from the framework would be to leverage the content of the document as unified vision to set and articulate engineering learning across grade bands to best provide the opportunity for children to engage in rigorous and authentic learning experiences to think, act, and learn like an engineer

## Development Process

Based on recommendations from the *National Academy of Engineering* reports, which have stated "the need for developing a framework (or taxonomy) of agreed upon engineering content knowledge for teachers through the involvement of content experts working with grade-level experts," AE3 initiated a "call to action" to build a community with a shared focus, vision, and research agenda to develop a coherent framework for P-12 engineering education in an effort to ensure that **every** child is given the opportunity to think, learn, and act like an engineer. This process, which launched in 2016, afforded education leaders a dynamic platform to (a) pursue a vision for P-12 engineering education, (b) establish a coherent curricular structure for the three dimensions of engineering learning, and (c) conduct research on the learning of engineering concepts/practices to better understand how to achieve engineering literacy for all.

### Phase 1 (Research & Investigation)

The first phase of the project (Research & Investigation) sought to engage experienced teachers and content experts in the development of the primary components of a viable engineering content taxonomy for use in secondary engineering programs. Specifically, the investigation pursued the establishment of agreed upon (1) core concepts and (2) sub-concepts for the development of progressions of learning to support the coherent study of engineering and support future work toward engineering standards development. To achieve these objectives, the AE3 team conducted a modified Delphi study, which included experts from the education and engineering communities. The Delphi technique attempts to build a consensus of opinion by asking experts a round of questions and then developing more refined questions that are returned to the respondents for multiple rounds of iteration. Accordingly, the experts were asked to identify and then rate important concepts and corresponding sub-concepts for both the knowledge and practice dimensions of engineering learning through a total of three rounds of questions (conducted anonymously through an online survey tool), concluding in a final round consisting of multiple focus groups for member checking and revising the results of the first three rounds:

- Round 1: Concept discovery (identifying important concepts and sub-concepts)
- Round 2: Concept prioritization
- Round 3: Concept rating
- Final Round: Concept Verifying and Refinement (involving focus groups)

Before the Delphi study was conducted, $AE^3$ conducted a literature review to establish a conceptual taxonomic structure for engineering concepts which is illustrated in Figure 1 to provide to the participants. The structure was founded on the synthesis of relevant literature

 

(Carr, Bennett, and Strobel, 2012; Custer and Erekson, 2008; Merrill, et al., 2009; NAE, 2009; 2010; Sneider and Rosen, 2009; etc.) as well as the National Academies' Taxonomy of Engineering (National Academies of Sciences, Engineering, and Medicine, 2017), the Fundamentals of Engineering Exams (National Council of Examiners for Engineering and Surveying, 2017), first-year engineering programs (Strimel, et al., 2018), and the Accreditation Board for Engineering and Technology disciplines of engineering, engineering technology, and computing (Engineering Accreditation Commission, 2016). The Delphi participants reviewed the conceptual taxonomic structure and then identified and prioritized the important concepts and sub-concepts for each component to serve as the foundation for the knowledge and practice dimensions of engineering learning (Note: The Habits of Mind dimension of engineering learning was not developed as part of this process as there was an abundant amount of literature defining these engineering habits). As perceived by the participants, the importance of each concept was measured on a scale from 1 to 6, with the higher number representing more important concepts.

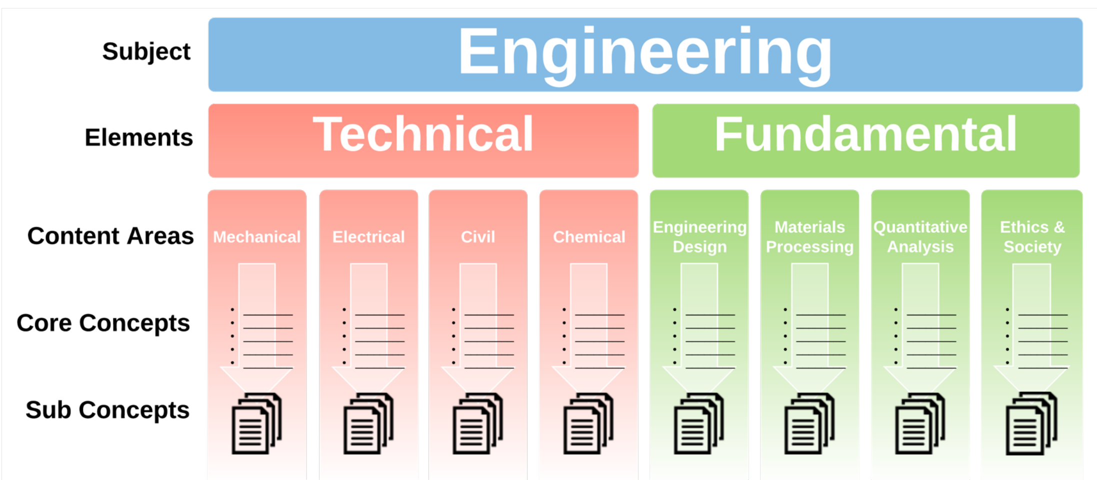


*Figure 1.* Potential Taxonometric Structure for the Knowledge and Practice Dimensions of engineering learning

A total of 40 participants—with various professional experiences—were selected and invited across secondary education, post-secondary education, and engineering-related professions (based on the recommendations of national organizations). The participants included teachers and administrators for secondary education; faculty members or administrators in engineering or teacher education programs; coordinators of P-12 engineering outreach; and technologists, engineers, scientists, or mathematician working in engineering-related professions. Also, professional association administration or leadership, curriculum specialists, state education administrators, and graduate students majoring in engineering and technology were invited to diversify the expertise for a content structure of P-12 engineering. Table 1 presents the overall participant backgrounds for each round of the study.

Table 1
Overall Invited, Round 1, 2, 3, and Final Participant Backgrounds

| Professional Experience | Invited | Round 1 | Round 2 | Round 3 | Final Round |
|---|---|---|---|---|---|
| **Secondary Education**<br>• Engineering/Technology Teacher<br>• Science Teacher<br>• Mathematics Teacher<br>• K-12 Administrator<br>• Other | 26 | 9 | 13 | 15 | 21 |
| **Post-Secondary Education**<br>• Engineering Faculty<br>• Teacher Education Faculty<br>• Science Faculty<br>• Mathematics Faculty<br>• Engineering Administrator<br>• Teacher Education Administrator<br>• Outreach Coordinator<br>• Other | 23 | 18 | 14 | 12 | 17 |
| **Professional**<br>• Engineering Technologist/Technician<br>• Civil Engineer<br>• Mechanical Engineer<br>• Electrical/Computer Engineer<br>• Biomedical Engineer<br>• Industrial Engineer<br>• Scientist<br>• Mathematician<br>• Other | 22 | 5 | 5 | 4 | 17 |
| **Other**<br>• Professional Association Administration/Leadership<br>• Outreach/Curriculum Specialist<br>• Other (State Education Administrator, Graduate Student) | 15 | 2 | 6 | 5 | 13 |
| **Total Participants** | 40 | 22 | 24 | 26 | 32 |

*Note.* Many participants crossed several of professional experience categories.

After the three rounds were completed and eight focus groups deliberated the results in the final round, an initial engineering taxonomy emerged. A summary of this taxonomy is provided on the next page (see Strimel, Huffman, Grubbs, Kim & Gurganus, 2020).

## Engineering Habits of Mind

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

## Engineering Practices

| | | |
|---|---|---|
| **Engineering Design** | • Problem Framing<br>• Information Gathering<br>• Ideation<br>• Prototyping<br>• Engineering Graphics | • Decision Making<br>• Project Management<br>• Design Methods<br>• Design Communication |
| **Material Processing** | • Measurement & Precision<br>• Manufacturing<br>• Fabrication<br>• Material Classification<br>• Joining | • Casting/Molding/Forming<br>• Separating/Machining<br>• Conditioning/Finishing<br>• Safety |
| **Quantitative Analysis** | • Computational Thinking<br>• Computational Tools<br>• Data Collection, Analysis, & Communication | • System Analytics<br>• Modeling & Simulation |
| **Professionalism** | • Professional Ethics<br>• Workplace Behavior/Operations<br>• Honoring Intellectual Property | • Technological Impacts<br>• Role of Society in Technological Development<br>• Engineering-Related Careers |

## Engineering Knowledge

| | | |
|---|---|---|
| **Engineering Sciences** | • Statics<br>• Mechanics of Materials<br>• Dynamics<br>• Thermodynamics<br>• Fluid Mechanics | • Mass Transfer & Separation<br>• Chemical Reactions & Catalysis<br>• Circuit Theory<br>• Heat Transfer |
| **Engineering Mathematics** | • Engineering Algebra<br>• Engineering Geometry & Trigonometry | • Engineering Statistics & Probability<br>• Engineering Calculus |
| **Engineering Technical Applications** | • Electrical Power<br>• Communication Technologies<br>• Computer Architecture<br>• Process Design<br>• Structural Analysis<br>• Environmental Considerations | • Hydrologic Systems<br>• Transportation Infrastructure<br>• Geotechnics<br>• Chemical Applications<br>• Mechanical Design<br>• Electronics |

**Phase 2 (Development & Testing)**

The second phase of the project (Development & Testing) sought to engage the engineering and education communities, including experienced teachers and content experts, in (a) refining of the engineering content taxonomy, (b) drafting hypothetical progressions of learning based on the established content taxonomy, (c) developing sample learning activities to teach the engineering concepts through socially-relevant and culturally situated contexts, (d) reviewing content and pedagogical practices through the lens of equity, (e) modeling best practices from P-12 engineering classrooms, and (f) implementing the resulting work for building and testing curriculum in partner school systems. These efforts were enacted to establish, refine, and validate the core components of this framework, including the concepts and practices for engineering learning. See Figure 2 for a graphic representation of the framework refinement process. The majority of these efforts were carried out through 3 action-oriented *Advancing Excellence in P-12 Engineering Education Symposiums* held at the Engineer's Club in Baltimore, MD. Each of these events had specific a topic and objective toward creating this framework and interacting with the pilot school system. A summary of these symposia is provided below and the agendas for each event can be found in the appendices.

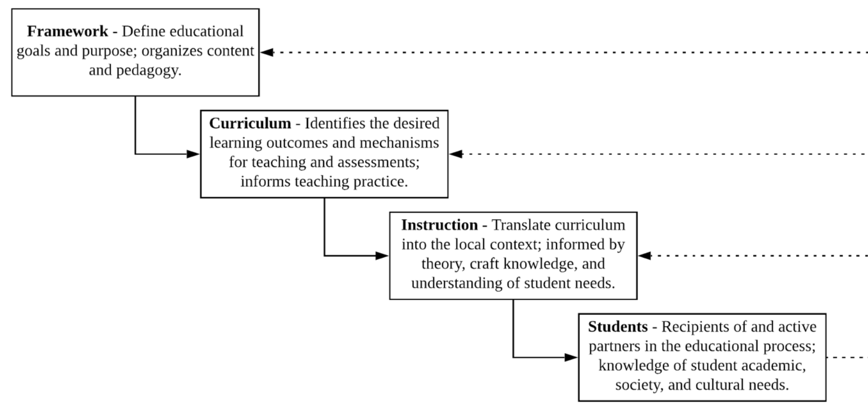

*Figure 2.* Framework Refinement Process.

- **Symposium 1: *Progressions of Learning for Engineering***
    - The first symposium focused specifically on the refinement of the engineering content taxonomy developed through the Delphi study and the conceptual development of hypothetical progressions of learning related to each concept within the taxonomy. Also, the participants heard from leaders regarding the state of P-12 Engineering Education from the state and national perspectives as well as leaders in educational equity. These speakers were provided time to serve as provocateurs to inform the development work of the symposium participants in order to establish the conceptual foundation for this framework.
- **Symposium 2: *Equity Through Engineering Curriculum & Pedagogy***
    - The second symposium focused specifically on ensuring that equity is at the forefront of this framework in regards to engineering curriculum and pedagogy. The symposium participants heard from national leaders in engineering education, industry, and curriculum development who served as provocateurs as they worked in groups to review/refine the hypothetical progressions of learning in engineering and create socially-relevant and culturally-situated engineering instructional activities that demonstrate how the authentic engineering concepts within this framework could be taught equitably. This development work was

 

also leveraged to inform the development of engineering curriculum for a designated pilot school.

- **Symposium 3: *The Engineering Framework***
  - The third symposium focused on informing the official development of this framework and receiving key feedback on its components from the P-12 engineering education community. During this symposium, participants heard from national leaders in regards to best practices for engineering curriculum, professional development, assessment, classroom implementation, and instructional tools in order to expand their knowledge about what P-12 engineering is, what it can look like, and what it can achieve. The participants then used this knowledge to provide feedback on the components of this framework and further inform the curriculum for the pilot school.

**Phase 3 (Synthesis & Writing)**

The third phase of this project (Synthesis & Writing) involved establishing a writing team to assemble the three years of input collected from the engaged P-12 Engineering Education community at the three symposia into a coherent, digestible, and practical framework usable by teachers and administrators, who may or may not have any training related to teaching engineering, that are on the frontlines of the classroom. This also included review and feedback from relevant stakeholders identified through ASEE. The result of this process are the components of this framework.

## Framework Components and Organization

The decision to organize the framework by dimensions of *Engineering Habits of Mind*, *Engineering Practices*, and *Engineering Knowledge* was based on the desire to align with and complement the structure of broadly adopted education frameworks. Specifically, the National Research Council's (NRC) *Framework for K–12 Science Education* (2012) and the *K–12 Computer Science Framework* (2016) served as a model for this framework. For example, the *Framework for K–12 Science Education* has three dimensions: *Disciplinary Core Ideas*, *Scientific and Engineering Practices*, and *Crosscutting Concepts* and the *K –12 Computer Science Framework* (2016) contains core concepts and practices with implicit cross-cutting concepts integrated throughout. Relatedly, this framework advocates that engineering education in grades P-12 be built around the three major dimensions of engineering learning which consists of the habits of mind, practice, and knowledge that unify the area of study through their application across engineering-related disciplines.

To inform the articulation of the three dimensions of engineering, this framework leveraged the engineering content taxonomy (see Strimel, Huffman, Grubbs, Kim & Gurganus, 2020) to aid in determining the totality of the field of engineering knowledge along with its component elements and their interrelationships. The concepts related to the dimensions of *Engineering Knowledge* and *Engineering Practice* serve as the categories that represent major content areas in the broad field of engineering. More specifically, the concepts of *Engineering Knowledge* represent specific content, found across engineering disciplines, to inform engineering practice while the core concepts of *Engineering Practice* represent the knowledge associated with performing a particular practice well and with increased sophistication. The identified sub-concepts in the engineering taxonomy enables the concepts to become less abstract and provide more in-depth content within the context of engineering. These sub-concepts for each of the concepts are pertinent for creating focused, coherent progressions of learning in engineering to help articulate instruction based on individual student needs. The concepts found in this document have been operationally defined in Framework for P-12 Engineering Learning.  However, it is important to note that the *Engineering Habits of Mind* were not defined in this way as they are the ways of thinking that, over time, are encouraged and rewarded throughout engineering experiences in order to orient a student's routine thought processes.