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Determining the Engineering Knowledge Dimension: What all High School Students Should Know to be Engineering Literate (Fundamental)

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Rationale and Background

The importance of engineering for P-12 learners continues to increase[1-6]. This growing interest can be attributed to the idea that engineering education can contribute to the general education of all students as well as inspire a more diverse, and workforce ready, populace to meet the needs of high-demand careers of the 21st century[2]. Engineering education is uniquely positioned to support interdisciplinary learning experiences to foster rich connections and further knowledge and skills of academic disciplines. The inclusion of engineering into P-12 education is now seen as an approach to address challenges facing the U.S. educational system[2,3,7]. The teaching of engineering in primary and secondary schools must be expanded to better prepare students with the skills necessary for economic success[2]. Recently, the political climate has followed suit. Legislative efforts have been proposed to award grants to state educational agencies and local educational agencies to support, develop, and implement formal and informal engineering education programs in elementary schools and secondary schools (H.R.4023 - Developing Tomorrow's Engineering and Technical Workforce Act, H.R.4023, 2017). Despite greater attention to the value, importance, and use of engineering for teaching and learning, few efforts have engaged in establishing an epistemological foundation for the study of engineering in P-12 classrooms[3,8]. Specifically, little research has been conducted to examine the engineering content and practices that are developmentally appropriate for P-12 learners[2,7,8].

Advancing Excellence in P-12 Engineering Education (AEEE) Project

The Advancing Excellence in P-12 Engineering Education (AEEE) project is an ongoing research venture to promote collaboration across the engineering and education communities to first, pursue a vision and direction for P-12 Engineering Education; and second, to develop a coherent and dynamic content framework for scaffolding the teaching and learning of engineering at the high school level. These efforts will be accomplished through a series of action-oriented activities and product developments as outlined in the AEEE initiation timeline (Figure 1).

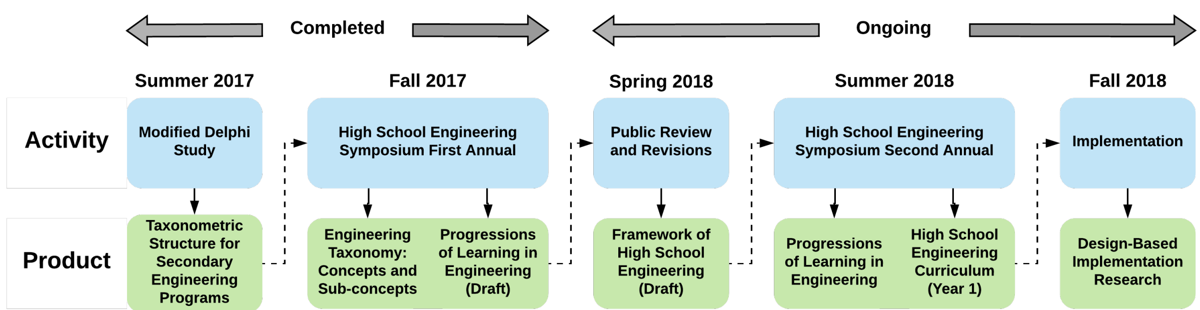

Figure 1: AEEE Initiation Timeline

The completion of the project activities will directly impact the formation of a high school engineering program of study to be implemented beginning in the Fall of 2018 at a large public-school system in the eastern United States. The activities of the AEEE project to this point have included the establishment of the *Taxonometric Structure for Secondary Engineering Programs* through a modified, three-round Delphi study and development of preliminary model for *Progressions of Learning in Engineering* (PLiE)[9,10]. To further the work and validate developed materials, the AEEE project held the first annual High School Engineering Education Symposium. This paper reports the methods and results of this three-day event.

High School Engineering Education Symposium

The High School Engineering Education Symposium provided a platform to complete two crucial AEEE project goals; (1) Stakeholder and expert revisions of the *Taxonometric Structure for Secondary Engineering Programs* and (2) establish writing teams and preliminary drafts of the *Progressions of Learning in Engineering*. To accomplish these goals, the symposium brought together 40 experts from the education, engineering education, technology education and engineering communities. Experts were invited based on participation from preceding Delphi study and recommendations from various stakeholders with an interest in the project (e.g. ASEE, ITEEA, State Departments of Education, local Universities). Participants were asked to find local funding to attend the symposium but were given the opportunity to apply for travel reimbursement where local funding was not available. All meals for the event were paid for through project sponsorship.

The symposium's format was a modified focus group research design and included guest speakers and workshop sessions. As described by Krueger and Casey[11], a focus group research design gives consideration to a) participant selection, b) the environment, c) the moderator and d) analysis and reporting. Participant selection ensure demographic variety in three primary ways. First was diversity of gender. Of the 40 participants, 19 were female and 21 were male. The second primary demographic was career experience (teacher, engineer, post-secondary). A majority of the participants were active high school teachers (6) or had previous experience as a classroom teacher (15). 19 participants had an engineering undergraduate degree with 11 having industry experience. 15 participants currently hold positions at post-secondary institutions, including colleges/schools of engineering, technology and education. Many participants crossed several of these demographics. The third characteristic of interest was regional location. As the AEEE project will impact a regionally located school system, participants were sought with a local investment or a national expertise. 24 participants resided within a day's driving distance of the local school system of focus.

The environment of the focus group symposium can be described by the physical location as well as the time given on each task. The focus group work took place at the Engineers Club in Baltimore, MD. This location had rooms for breakout focus discussions and a shared presentation room. The agenda included work sessions and guest speakers. In addition to the participants, a number of speakers were invited to share their expertise in diversity, industry needs and state departments of education. The speakers were used to provide project context and act as provocateurs to further discussion. Workshop sessions included the refinement of previously developed work, focused discussions and authoring of new materials.

The focus groups were moderated by team leads and project co-directors. No additional analysis was performed by this paper's authors on the results of this work beyond formatting. Reporting of the results are presented as a formatted tables and figures.

On day one of the symposium, the participants were briefed on the project overview, goals and accomplishments to date. Guest speakers from two state departments of education described their agency's approach to engineering education and a need for further establishment of a coherent and consistent framework for student learning. During the workshop session, participants were given the opportunity to provide feedback on a literature review presenting two of the three Dimensions of Engineering Literacy (Figure 2).

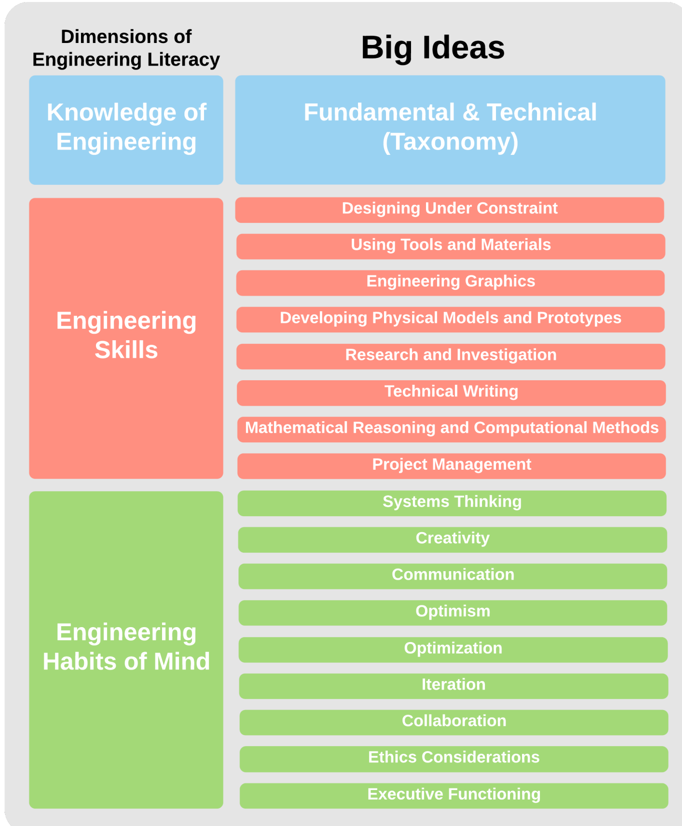

Figure 2: Engineering Skills and Habits of Mind

Engineering Skills were defined as skills students should practice and master to become Engineering Literate. Engineering Habits of Mind were described as traits or ways of thinking that affect how a student looks at the world or reacts to a challenge. Each Engineering Habit of Mind and Engineering Skill was posted on an 18"x24" poster board displayed around the room. Participants completed a "gallery walk'" to provide feedback using stickie notes and the following guidelines.

- Pluses (+) – What do you like about the Skill/Habit? What are the positives of including for high school students?
- Potentials (&) – What other good things might happen by including the Skill/Habit? What might it lead to?
- Concerns (-) – What are the limitations/misconceptions/dangers of including the Skill/Habit?
- Outcomes (O) – Ideas that maximize the Pluses and Potentials and mitigate/overcome the concerns

The feedback was recorded for later usage and poster boards remained viewable for the entirety of the symposium. The intent of this activity on the first day of the symposium was to review a synthesis of research completed to this point about what and how engineering should be taught at the P-12 level. Furthermore, the activity helps establish a need to investigate the engineering knowledge dimension that, up to this point, has seen only preliminary developmental efforts.

Days two and three of the symposium saw a review and refinement of concepts and sub-concepts within the Fundamental Element of the *Taxonometric Structure for Secondary Engineering Programs* as developed by the Delphi study (Figure 3 provides the established taxonometric structure). The *Taxonometric Structure for Secondary Engineering Programs* was founded on the dimensions of engineering literacy and the synthesis of relevant literature[2,7,12-15] as well as the National Academies' Taxonomy of Engineering[8], the Fundamentals of Engineering Exams[16], first-year engineering programs[17], the Accreditation Board for Engineering and Technology disciplines of engineering, engineering technology, and computing[18] and the ITEEA Engineering Endorsement Responsibility Matrix. The Delphi participants reviewed the taxonometric structure and identified and prioritized the core concepts and sub concepts for each content area to serve as the foundation for the knowledge dimension of engineering literacy.

Participants were organized into four focus groups, one for each Fundamental Content Area: Quantitative Analysis, Engineering Design, Ethics and Society, and Materials Processing and then each Technical Content Area: Mechanical, Electrical, Chemical, Civil. Each focus group was comprised of at least one high school teacher and one engineer or engineering educator. Participants were asked to revise the core and sub concepts for each content area as a group based on the following guiding questions:

1) Is this a fundamental/technical core concept or sub-concept of engineering? Justify through narrative.
2) Is this core concept or sub-concept appropriate for high school learners? Justify through narrative.
3) How is this core concept or sub-concept connected to one or more Engineering Skill(s) and/or Engineering Habit(s) of Mind?

On day two, participants were given two and a half hours to complete the task for the Fundamental Elements. On day three, participants were given two and a half hours to complete the task for the Technical Elements.

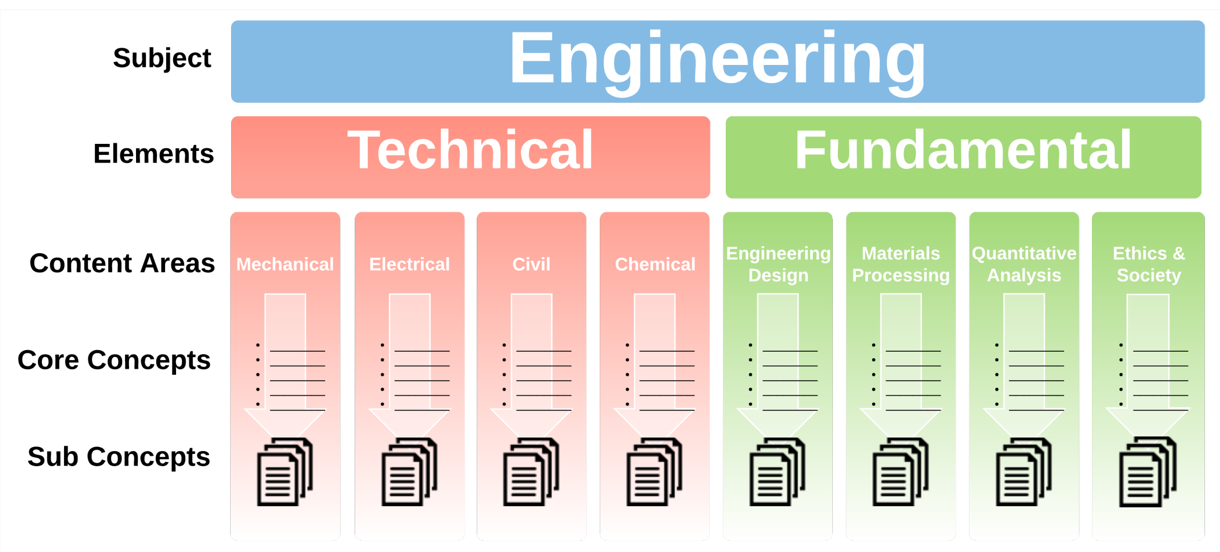

Figure 3: Taxonometric Structure for Engineering Knowledge

Results from Taxonomy Focus Groups

There were two major pieces of foundational work produced as part of the focus group discussions and work sessions. The first was revised versions of the Fundamental and Technical elements of engineering knowledge and a draft progression of learning in engineering (PLiE). The revised Fundamental Elements concepts and sub-concepts are presented in Table 1[9,10]. The revised Technical Elements concepts and sub-concepts are presented in Table 2[9,10].

Table 1: *Revised Fundamental Core & Sub Concepts of Engineering*[9,10]

Engineering Design	Material Processing	Quantitative Analysis	Ethics & Society
Problem Scoping ● Identifying Design Parameters ● Problem Statement Development **Research** ● Information Gathering ● Data Collection and Organization Methods ● Information Quality Assessment **Ideation** ● Spatial Visualization (e.g. sketching) ● Divergent Thinking (e.g. brainstorming) ● Convergent Thinking (e.g. functional decomposition) **Prototyping** ● Testing and Modification (virtual and physical) ● Material Selection ● Manufacturing Processes ● Computer Aided Design and Manufacturing **Decision Making** ● Evidence/Data/Reason-Driven Decisions ● Apply STEM principles ● Balance Trade-offs ● Use Decision Making Tools ● Group Decision Making **Design Communication** ● Technical Writing ● Presentation Tools ● Information Graphics ● Visual Design **Project Management** ● Initiating and Planning ● Scope, Time and Cost Management ● Risk, Quality, Teams, and Procurement **Design Methodologies** ● Iterative Cycles ● User Centered Design ● Systems Design ● Troubleshooting ● Reverse Engineering **Engineering Graphics** ● Engineering Drawings ● Dimensioning and Tolerances ● 2D CADD ● 3D Parametric Modeling	**Measurement & Precision** ● Measurement Instrumentations ● Accurate Layout & Precise Measurement ● Units & Significant Figures **Manufacturing** ● Design for Manufacture ● Additive Manufacturing ● Subtractive Manufacturing **Fabrication** ● Tool Selection ● Product Assembly ● Hand Tools ● Equipment & Machines ● Quality & Reliability **Material Classification** ● Metals & Alloys ● Composites ● Polymers ● Ceramics **Joining** ● Fastening ● Soldering ● Adhesion ● Welding ● Brazing **Forming** ● Forging ● Extruding ● Rolling **Machining** ● Drilling ● Cutting ● Milling ● Turning ● Grinding ● Reaming **Finishing** ● Adhesion ● Grinding ● Polishing ● Burnishing **General Safety** ● Laboratory Guidelines ● Machine Specific Safety ● Attire and Equipment	**Computational Thinking** ● Programming & Algorithms (including flowcharting) ● Programming (script programming languages) ● Software Design, Implementation, & Testing **Computational Tools** ● Spreadsheet Computations (e.g. MS Excel) ● Scripting Languages (e.g. MATLAB, LabView) ● Data Visualization (e.g. charts, graphs, etc.) **Data Collection, Analysis & Communication** ● Techniques of Data Collection (e.g. sampling methods) ● Data-Driven Decisions ● Creating Graphs & Documents ● Reporting Data **Systems Analysis** ● Inputs & Outputs ● Feedback Loops ● Optimization ● Product Life Cycle **Modeling & Simulation** ● Physical Models ● Computational Simulations ● Mathematical Models ● Failure Analysis and Destructive Testing ● Design Validation through Calculations **Engineering Algebra** ● Recognizing, Selecting, and Applying Appropriate Algebraic Concepts & Practices ● Manipulation of Algebraic Equations ● Curve Fitting ● Linear Algebra ● 2D & 3D Coordinate Systems **Engineering Geometry** ● Recognizing, Selecting, & Applying Appropriate Geometric Concepts & Practices ● Manipulation of Geometric Equations ● Trigonometry ● Vector Analysis **Engineering Statistics and Probability** ● Recognizing, Selecting, & Applying Appropriate Probability & Statistics Concepts & Practices ● Basic Statistics (normal distributions, percentiles) ● Probability ● Regression ● Inferential Statistics & Tests of Significance (e.g. t-tests, statistical tolerance) **Engineering Calculus** ● Differential & Integral Calculus ● Differential Equations & Multivariable Calculus	**Professional Ethics** ● Morals, Values, & Ethics Continuum ● Code of ethics ● Legal vs. Ethical considerations **Professional Practice** ● Public Health, Safety, & Welfare ● Responsible Conduct of Research ● Workplace Culture ● Ethical Business Operations ● Agreements & Contracts ● Public Policy and Regulation ● Professional Liability **Honoring Intellectual Property** ● Patents, Copyright, & Licensure ● Referencing Sources ● Intellectual & Physical Property **Impacts of Technology** ● Environmental Impacts ● Global Impacts ● Social Impacts ● Culture Impacts ● Economic Impacts ● Individual Impacts ● Political Impacts **Role of Society in Technology Development** ● Addressing Societal Needs & Desires ● Design Sustainability ● Technology Design in Cultures ● Scaling of Technology ● Appropriate Technology ● Inclusion & Accessibility ● Public Participation in Decision Making **Careers in Engineering** ● Professional Licensing ● Recognition of Engineering-Related Careers ● Trade Organizations ● Entrepreneurship

Table 2: *Revised Technical Core & Sub Concepts of Engineering*

Mechanical	Electrical	Civil	Chemical
Engineering Sciences for Mechanical Engineering ● Force Systems ● Equilibrium ● Inertia ● Friction ● Centroids & Moments ● Particles ● Rigid Bodies ● Newton's Second Law ● Work and Energy ● Impulse-momentum **Mechanics of Materials** ● Stress Types (axial, bending, torsion, shear) & Transformations ● Material Characteristics, Properties, & Composition ● Stress-Strain Analysis ● Static Equilibrium ● Material Deformations ● Material Equations ● Phase Diagrams ● Heat Treating **Dynamics & Vibrations** ● Scalars ● Vectors ● Resistance ● Gears **Mechanical Design** ● Manufacturing Processes ● Machine Elements (springs, pressure vessels, beams, piping, cams and gears, threads and fasteners, power transmission, electromechanical components) ● Machine Control **Elector-Mechanical Systems** ● Basic Electricity ● Circuits ● Motors & Generators ● Electric Charge ● Magnetism **Fluid Mechanics** ● Fluid Properties ● Lift, Drag, & Fluid Resistance ● Fluid Statics & Motion (Bernouili's equation) ● Hydraulics ● Pneumatics **Thermodynamics** ● Thermodynamic Properties, Laws, & Processes ● Energy Transfer ● Thermal Equilibrium ● Thermal Resistance ● Gas Properties ● Power Cycles & Efficiency ● Heat Exchangers ● HVAC Processes ● Psychrometics **Emerging Mechanical Engineering** ● Mechatronics & Robotics ● Bio-Mechanics ● Nanotechnology ● Ocean Engineering	**Engineering Sciences for Electrical Engineering** ● Properties of Materials (Chemical, Electrical, Mechanical and Thermal) ● Current, Voltage, Charge, Energy, & Power ● Forces (e.g. charges, conductors) ● Voltage and Work **Electrical Power** ● Force ● Motors & Generators ● Electrical Materials ● Electro-magnetics ● Voltage Regulation ● Transmission & Distribution **Circuit Analysis** ● Series & Parallel Equivalent Circuits ● Ohm's Laws & Kirchhoff's Laws ● Power & Energy ● Resistance, Capacitance, & Inductance ● Wage forms ● Analog vs. Digital Signals **Electronics** ● Instrumentation & Components (physical components & measurement devices) ● Semiconductor ● Amplifiers **Control Systems** ● Sensors ● Closed and Open loop & Feedback (systems – system response) ● Block Diagramming **Digital Systems** ● Programmable Logic Devices ● Logic Simplification (Boolean logic, K-mapping) ● Number systems ● Logic state & Gate arrays ● State Machine Design (microcontrollers/programming) **Communication Technology** ● Digital Communications ● Telecommunications ● Fiber Optics (photonics) **Computer Systems** ● Computer Hardware ● Computer Software ● Integrated Circuits ● Processors & Microprocessors ● Interfacing ● Algorithms ● Networks ● Memory ● Programming Languages **Emerging Fields in Electrical Engineering** ● Biomedical Engineering Applications (instrumentation, imaging, biometrics) ● Virtual system ● Artificial Intelligence ● Cybersecurity	**Engineering Sciences for Civil Engineering** ● Force ● Equilibrium ● Inertia ● Friction ● Centroids & Moments ● Rigid Bodies ● Resultant Calculations ● Shear & Moment Diagrams **Hydrologic Systems** ● Hydrology & Hydraulics ● Water Distribution & Collection Systems ● Watershed Analysis ● Open Channel ● Closed Conduits (Pressurized) ● Pumping Stations ● Laboratory & Field Tests **Structural Analysis** ● Physical Properties of Building Materials ● Deflection ● Deformations ● Column & Beam Analysis ● Mohr's circle (2D graphical representation of the transformation law for the Cauchy stress tensor) ● Implementation of Design Codes **Infrastructure** ● Street, Highway, & Intersection Design ● Transportation Planning & Control (safety, capacity, flow) ● Traffic Design ● Pavement Design **Surveying** ● Topographical Surveys ● Route Survey ● Leveling ● Coordinate System **Project management in Civil Engineering** ● Project Planning & Management ● Economics ● Safety ● Project Delivery ● Human Resource Management ● Verifying Local Codes **Geotechnical Engineering** ● Laboratory & Field tests ● Erosion Control ● Geological Properties & Classifications ● Soil Characteristics ● Bearing Capacity ● Drainage Systems ● Foundations & Retaining Walls ● Slope Stability **Environmental Engineering** ● Ground & Surface Water Quality ● Wastewater Management (disposal) ● Environmental Impact Regulations & Tests ● Natural Systems	**Engineering Sciences for Chemical Engineering** ● Applications of Inorganic Chemistry ● Applications of Organic Chemistry (e.g. Biofuels) ● Chemical, Electrical, Mechanical and Physical Properties (including potential hazards) ● Material Types and Compatibilities ● Corrosion ● Membrane Science **Chemical Reaction & Catalysis** ● Reaction rate, Rate Constant, & Order ● Conversion, Yield, & Selectivity ● Chemical Equilibrium **Fluid Mechanics & Dynamics** ● Bernoulli's Principle ● Flow ● Pumps, Turbines, & Compressors ● Fluid Properties ● Heat Transfer ● Conductive, Convective, & Radiative Heat ● Heat Transfer Coefficients **Energy** ● Work, Energy, & Power ● Energy Balance ● Fuels ● Energy Transfer **Thermodynamics** ● Thermodynamic Properties, Laws, & Processes ● Equilibrium ● Gas Properties ● Power Cycles & Efficiency **Mass Transfer & Separation** ● Molecular Diffusions ● Separation Systems ● Equilibrium State Methods ● Humidification & Drying ● Continuous Contact Methods ● Convective Mass Transfer **Process Design** ● Process Controls & Systems ● Process Flow, Piping, & Instrumentation Diagrams ● Recycle & Bypass Processes ● Industrial Chemical Operations **Biological/Chemical Applications** ● Bio-molecular Engineering ● Biotechnology ● Biochemical Engineering ● Pharmaceuticals

After refining the taxonometric structure, the groups were asked to complete one draft progression of learning in engineering for each core concept (Figure 4). A learning progression, defined as "a sequenced set of subskills or bodies of enabling knowledge that, it is thought, students must master en route to mastering a more remote target curriculum aim"[19] (p. 24), is necessary for the planning and assessment of learning engineering concepts. With progressions of learning, educators can better understand how students develop and demonstrate knowledge and skills for a certain subject enabling the teaching and learning process to function properly. Learning progressions are typically presented as "visual and conceptual maps that explain how students might move from simpler to more sophisticated understanding within a subject area"[20] (p.3). Thus, learning progressions enables teachers not only to analyze and respond to students' learning needs but also to align their instruction with new standards[20].

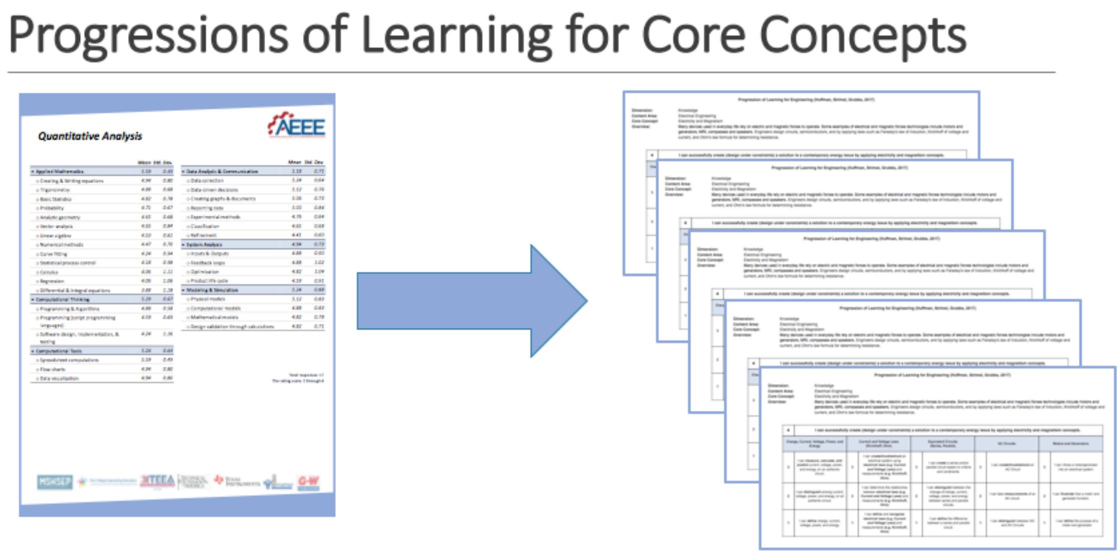

Figure 4: PLiE Description

Magana[21] described five characteristics of learning progression frameworks that provided guidance for the creation of a learning progression framework for engineering education. A *Progression of Learning in Engineering* (PLiE) template was developed based on consultation with a variety of engineering education experts, including teachers, professors, and industrial practitioners. The PLiE framework along with the revised taxonomy for secondary engineering were employed by the symposium participants to draft progressions of learning for secondary engineering that progress across different depths of student understanding from basic to advanced, in relationship to the habits of mind and skills dimensions of engineering literacy. Table 3 presents an example PLiE for mechanics of materials for the mechanical content area.

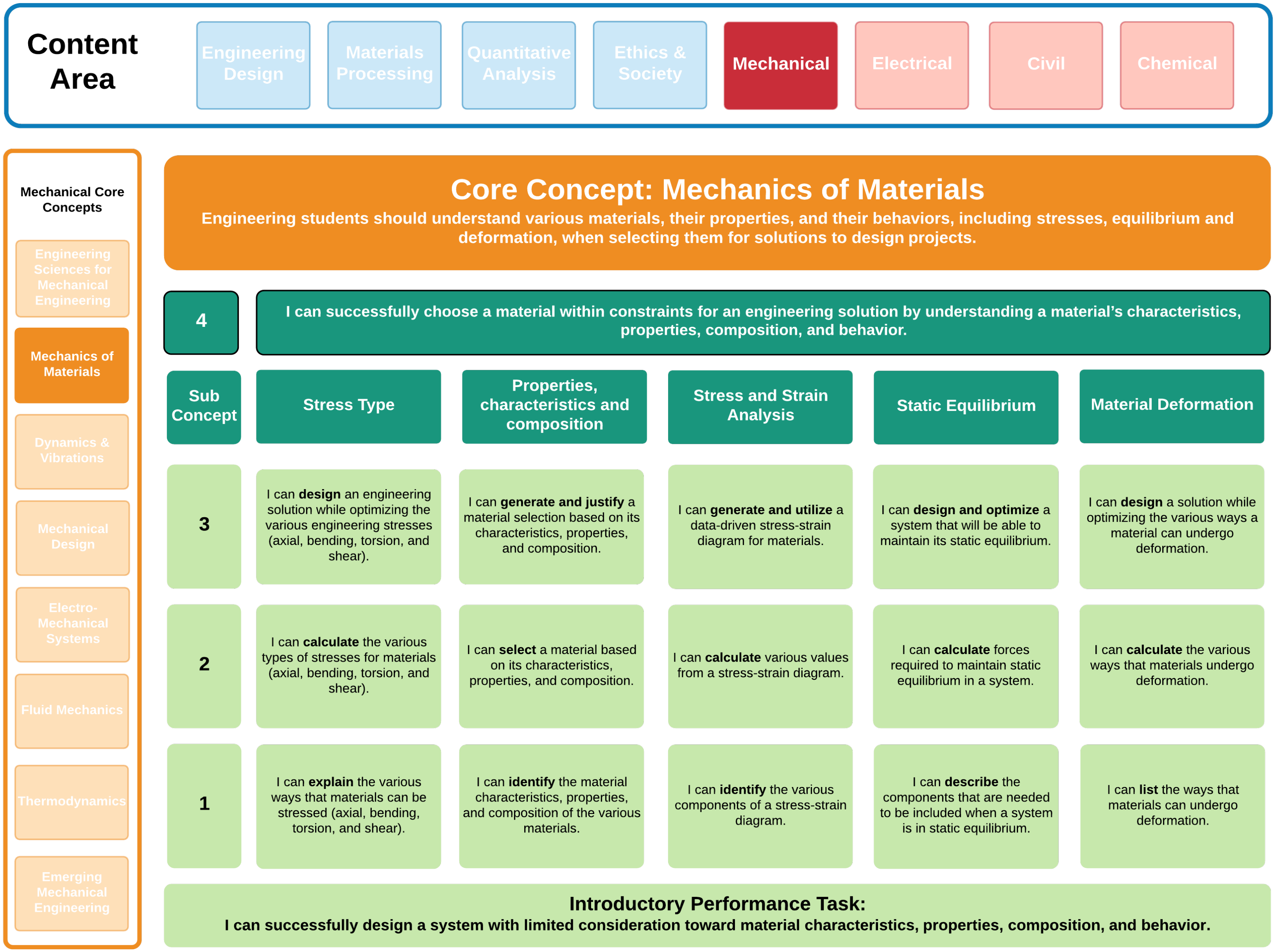

Figure 5. Example Progression of Learning in Engineering (PLiE)

Conclusion

The results presented in this paper are important to the development and refinement of what types of learning, related to engineering, are appropriate for high school students. While the concepts and sub-concepts defined in the revised *Taxonometric Structure for Secondary Engineering Programs* are no means exhaustive to all the types of engineering learning that occurs in P-12 engineering classrooms, they are complementary to and expand upon the concepts presented as "engineering" in technology (Standards for Technological Literacy) and science (NGSS) learning standards. As evident in the concepts and sub concepts and through the draft Progression of Learning in Engineering, science, math and technology knowledge are natural companions to the interdisciplinary nature of teaching engineering. Quantitative analysis, materials processing and engineering sciences frame a STEM classroom with engineering as the driving epistemological foundation and context for meaningful learning. Further research as part of the AEEE project will determine the impact of this framework on high school students and teachers and inform future versions. Efforts will be made to seek complementary guidance for the preparation of engineering teachers from sources such as the Standards for Preparation and Professional Development for Teachers of Engineering[22].

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