Perspectives on K-12 Engineering

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What is engineering? Why should students learn about engineering? How can it help them? To answer these questions we need to move beyond the workaday definitions that describe the professional practice of engineering, to the overall characteristics of engineering, the habits of mind and the engineer's way of viewing the world. Notice that the word engineer can be a noun or a verb. One can be an engineer, one can engineer a solution. The etymological root lies in the Latin word, *ingeniare*, to devise or design. The definition advanced by ABET is that "engineering is the creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works utilizing them singly or in combination." Webster's College Dictionary provides the following definition— "the practical application of science and mathematics, as in the design and construction of machines, vehicles, structures, roads and systems." These definitions belie the uniqueness of engineering, its body of thought, and the methodology, that it employs. Building on the ideas of C.P. Snow's *The Two Cultures*, engineers are optimists, they believe they can improve a design, create a solution, solve a problem; it is an outlook inherent to the profession, embedded in the engineering educational system.

To help us gain greater perspective, the information in Table 1 seeks to contrast the differences between math, science, engineering and social science/humanities. Of course these are thumbnail sketches, but they can highlight the differences between disciplines and help in thinking about the overarching themes that define engineering, noun and verb. Science is the study of the natural world, a discipline engaged in discovering the whys and wherefores of natural phenomena. There is a process for this investigation, scientific inquiry, in which a hypothesis is posed and logical investigations are undertaken to confirm or deny the hypothesis. Mathematics has its own philosophy and patterns. It is often used by engineers and scientists to model designs or represent natural phenomena, such as Newton's second law of motion, $\mathbf{F} = m\,\mathbf{a}$. There are rules of mathematical analysis, theorems, that allow us to manipulate such equations. A publication by the National Research Council, *Helping Children Learn Mathematics*, discusses the big ideas and habits of mind needed to be mathematically successful. The social sciences and humanities provide an entirely different view of the world, a world shaped by human perceptions and understandings. For instance, a novel or a political or social event can by analyzed from many different perspectives. There is no correct answer, but justified opinions.

Engineering	**Science**	**Mathematics**	**Social sciences and humanities**
Study of the human-made world	Study of the natural world	Study of mathematical constructs	Study of human mind and perception
Engineering design	Scientific inquiry	Mathematical analysis	Rhetoric and criticism
Iterative design process, optimum solution	Hypothesis testing and evaluation	Theorems, proofs, rational constructs	Eclectic methods, comparative values
Artifact produced	Theory confirmed	Theorem validated	Opinion rationalized

Table 1 Comparison between different fields of thought.

Engineering uniquely connects all these disciplines. In creating the human-made world, engineers must use knowledge from science, mathematics and social sciences and humanities. In contrast to scientific inquiry and mathematical analysis, engineering design does not seek a unique or correct solution, but rather seeks the best or optimum solution after a variety of factors are weighed, such as cost, materials, aesthetics, and marketability. The design process is iterative, creative, nonlinear. The solutions are tempered by our societal values. Hence, the optimal solution for one person may not be the optimum solution for another. Because we can bring our values to our design solutions, engineering design can be a very engaging pedagogical strategy.

Engineering becomes a way of understanding the human-made world, how it was created, how it functions and how it might be changed. Engineers realize that what has been made can be improved. Even if it were optimum at a moment in time for the specifications and constraints that were imposed, new technologies, new opinions, new perspectives allow for different solutions. This is a very empowering feature of engineering and this is in significant contrast to scientific and mathematical understandings, where hypotheses and theorems may be refined, but in the main they remain unalterable.

In our discussion of K12 Engineering we need to be able define a variety of terms; we are using the following definitions:

Engineering — creating the human-made world, the artifacts and processes that never existed before. This is in contrast to science, the study of the natural world. Most often engineers do not literally construct the artifacts, they provide plans and directions for how the artifacts are to be constructed. Artifacts may be as small like a hand calculator or large like a bridge. They also design processes, the processes may be those used in chemical and pharmaceutical industries to create chemicals and drugs, to directing how components are put together on an assembly line, or indicating how checks are to be processed in banking.

Technology — the artifacts and processes.

Technology Education — the study of the human-made world, its artifacts and processes.

Engineering Design Process — the iterative process for creation and manipulation of the human-made world. The process combines knowledge and skills from a variety of fields with the application of values and understanding of societal needs to create systems, components, or processes to meet human needs. Initialized by problem definition, followed by clarity of the specifications that the designed product must meet, the open-ended engineering design process optimizes competing needs and constraints, and uses modeling and analysis to drive the creation of new engineered solutions to serve humankind.

Engineers use **modeling** as a way to better understand what an actual artifact or process is experiencing. Consider a wooden plank used as a foot bridge across a stream. An engineer might be asked to predict whether or not the plank would break if subjected to a certain load. The engineer creates a **representational model** of the plank, including its size, assumptions about physical properties such as Young's modulus and yield stress, about property variation, and about how the plank is secured on the banks of the stream. Using the representational model, the engineer creates a free-body diagram and from the free-body diagram develops a **mathematical model** based on laws of mechanics. The accuracies of the representational model and the mathematical model determine how valid the predictions are. In the design process engineers create representational models of solutions and then mathematically characterize (model) them , e.g. free-body diagrams, to predict behavior.

In K-12 Engineering modeling is the combination of representational models, which may be drawings or three-dimensional renditions, and mathematical models based on or incorporated with the representational models. For instance, in fourth grade students could design a scaled version of a classroom. They would create scale drawings which would later be transferred to three-dimensional renditions of the design. The renditions could be made of cardboard. So there is a balance between the physical representational model and the mathematical model. In K-12 Engineering, particularly in the K-5 grades, the physical representational model will have certain attributes that are mathematically determined. As the students gain greater knowledge and skill, the mathematical modeling aspect can increase in sophistication. In 11th and 12th grades, students could represent actual electric and electronic circuits with circuit elements-resistance, capacitance, inductance, voltage and current sources-and then use mathematical models of the circuit elements to predict behavior. In design students would not construct the circuit first, initially they create a design they think will accomplish the desired goals, then representationally and mathematically model it. If the goals are achieved, then the actual circuit is constructed and tested to determine if the modeling (both types) was accurate.

Optimization—The process of improving each alternative design, or improving each part of a design, is called **optimization**. Often, different alternatives will be better in different ways. For example, one material may be stronger, but a second material may cost less. When choosing the best solution, normally requires trade-offs. That is, one must give up one desirable thing for another. In such cases, deciding which criteria are the most important helps in determining the best solution to the problem. The idea is to decide upon a design that best meets the specifications, fits within the constraints, and has the least number of negative characteristics.

Specifications—Specifications are the performance requirements, or output requirements, the design solution must fulfill. The design specifications for toothpaste might include that it cleans plaque form teeth, tastes good and can be squeezed easily out of a tube. A design specification for a certain type of car might be that it can accelerate from 0-60 mph in under ten seconds. Design specifications often include safety considerations. Stating that a passenger elevator must have a safety factor ten times greater than the load it is expected to carry, or that the front of a car will not be damaged after a crash of 5 mph are specifications the design must meet.

Constraints—Constraints are limitations imposed upon the design solution. Constraints are often related to resources such as the materials the designer is able to use, how much money a finished product can cost, or how much time can be devoted to producing it. Other limitations can relate to the availability of certain kinds of workers or by the need to limit negative effects of the design on the environment.

The *Standards for Technological Literacy* (2000) and *Project 2061* (1993) discuss the designed world and learning outcomes for K-12 associated with the technology education perspective. Certainly design plays an important role, as do ethics and the impact of technology on society. In addition, technical content, such as transportation systems and manufacturing systems, are viewed as important to know. The idea of systems thinking is supported and the connections made to natural and mathematical systems.

Engineering design is not trial-and-error gadgeteering. Engineers use their knowledge of science and engineering science to understand what is happening physically, their use of mathematics to create models that may be analyzed, and their understanding of prior technological solutions so they can innovate. Then they create design solutions. This is in contrast to the process used by inventors who may gadgeteer, arriving at a workable solution that they can patent or manufacture. The use of modeling, with its inherent predictive analysis, is one of the significant differences between engineering and technology education, and engineering and art.

Engineering design and the design process are inherent to engineering, as the roots of the word engineer are linked to the design process. But what of concepts like optimism and creativity? We need a framework that provides us with a way to visualize/describe the various attributes of engineering habits of mind (visualization, creativity, connecting science, mathematics, social sciences and humanities, optimism, how things work, systems thinking) and engineering practice (engineering design including optimization, specifications and constraints, societal impacts, modeling).

The following is a list of various aspects of engineering that could be included in K-12 education.

Engineering Habits of Mind	**Engineering Design**
Visualization	Design informed by knowledge and skill
Creativity	Optimization, trade-offs
Connections to S, M, SS/Hum	Modeling, predictive analysis
Optimism	Ethics, societal impacts
Technology (how things work)	
Systems thinking (subsystems, feedback)	

The National Research Council uses the concept of strands of knowledge as a way to visualize the content areas in mathematics and science. The listing above could be conceptualized as six strands, indicated below in Figure 1. There are many connections between the Engineering Habits of Mind and Engineering Design, some are indicated.

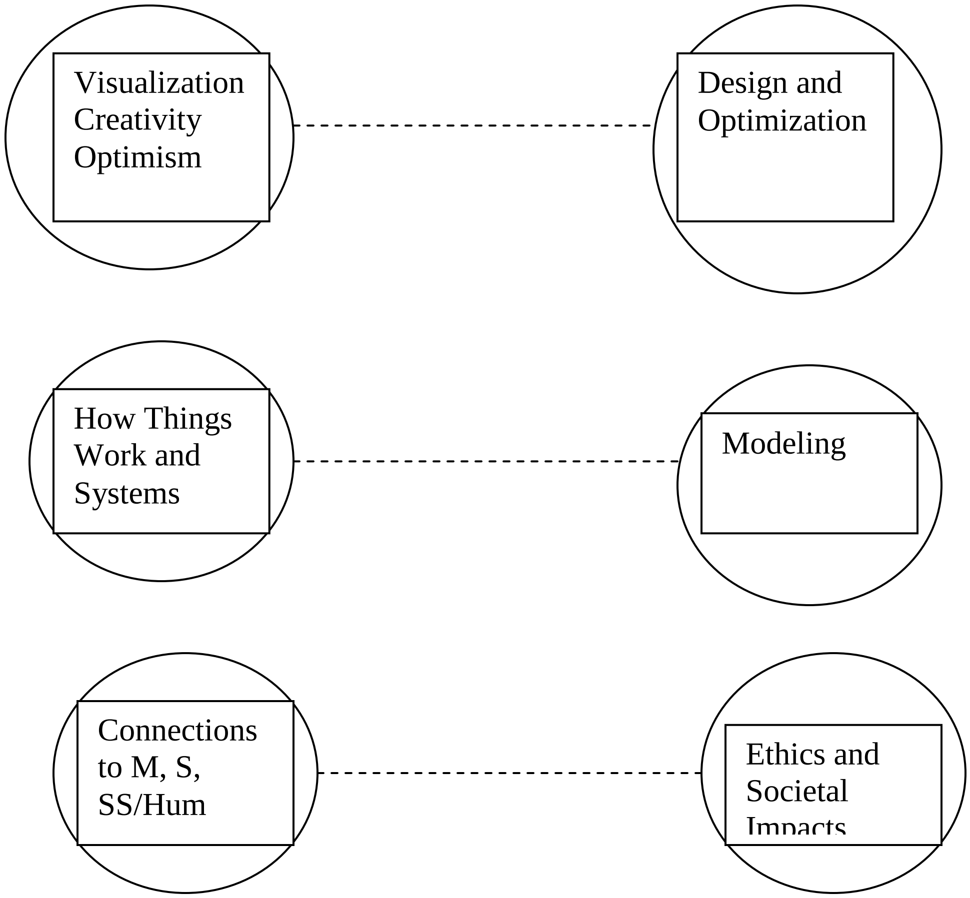

Figure 1 Strands of K-12 Engineering Content Knowledge

K-12 Engineering for All Students

In thinking about K-12 Engineering for all students, we need to consider children's developmental capability, what the classroom environment typically is and what the expectations are in terms of educational objectives. The K-12 spectrum is often divided into grades K-5, 6-8, and 9-12 and Table 1 indicates what how engineering might appear at different grade levels.

Grades K-5	Grades 6-8	Grades 9-12
At these grades students are primarily in self-contained classrooms with their teacher. The general focus of education is on literacy and math reasoning. There often are specialists for	At these grades students often move as a class cohort, changing teachers for different content areas. The general focus remains on literacy and math, but broadens to include social studies and science.	At these grades students move as cohorts and as individuals, as they begin to tailor their educational programs. There is expanding accountability in science and social science and continuing

science, art and physical education. It is recommended there be an Elementary Engineering K-5 specialist as well to support the classroom teacher. In this role, the specialist will help develop curriculum that explains the human-made world, how things work, systems thinking, societal impacts of technology. There could be design projects that support other curricular areas, such as creating robots from cardboard boxes and paper rolls in kindergarten that support measuring, to creating models of buildings in fifth grade that must meet certain volume and surface area requirements. It is also possible to use materials, such as *Engineering is Elementary*, as replacement science activities, though the thrust of NAE K-12 effort is not selling engineering, but using the pedagogical strengths that engineering brings to develop student knowledge in core academic disciplinary areas.	There may be elective offerings. It is recommended there be a secondary education Engineering Specialist who will have two roles, one analogous to that of the K-5 Engineering Specialist and the other role in providing a year-long course for all students in Engineering/Technology education. This course could be similar to middle school ET courses that currently exist, with strong connections to grade level appropriate math and science. Much of the content of these courses are design-based projects. The projects begin to use some modeling for predictive analysis. Support to academic areas can include information re societal impacts, as well as mini-design projects. There could be some design-based science labs, replacing existing science experiment labs.	accountability in language arts and mathematics. It is recommended there be a secondary education Engineering Specialist who will have two roles, one analogous to that of the K-5 Engineering Specialist and to provide a year-long course for all students in Principles of Engineering. This course would focus on case studies and these would feature societal impacts and ethics. For instance, there could be environmental impact case studies re development and ergonomic design considerations in developing emergency shelters. Gathering and using data in the case studies will be important, as well as modeling the solution prior to prototype design. Support to academic areas can include information re societal impacts, as well as mini-design projects. There could be some design-based science labs, replacing existing science experiment labs.

Table 1 Engineering at different grade levels

Contrasting K-12 Engineering with K-12 Science.

According to *Taking Science to School* (NRC, 2007), the following themes are necessary for students to be proficient in science. They should

1) know, use and interpret scientific explanations of the natural world;
2) generate and evaluate scientific evidence and explanations;
3) understand the nature and development of scientific knowledge; and
4) participate productively in scientific practices and discourse.

How is science currently taught? What are the attributes at the different grade levels? In general, there is more focus on living things than there is on inanimate matter. Children begin to learn about themselves and their interactions with the natural world around them. As this progresses to middle school, the physical world becomes more important, but less so than the living world. Science is primarily qualitative at the elementary and middle-school levels. In high school, specialty content areas in biology, chemistry, physics, and earth science are often included in student requirements. There is an increase in quantitative reasoning in chemistry and physics; earth science and biology often are relatively more qualitative. All require laboratory experiments and reports, which can include data analysis and explanations, particularly so at the high school level.

The information in Table 2 is based on the New York State Core Science Standards which match national science standards.

Grades K-4	**Grades 5-8**	**Grades 9-12**
Science is often taught by the classroom teacher, perhaps 2 periods per week. In general, elementary school teachers have had little science (or math) at the college level. Some more affluent schools have science specialists who meet with the class; there may be science specialists to assist classroom teachers. There may be science kits (e.g. Foss) provided and teachers follow the provided guide. The goal is the understand major themes in the natural world such as earth and celestial surroundings, weather and climate, properties of matter, energy forms, living and non-living things, genetics, evolution, reproduction.	Science is taught by a science specialist, ideally certified in a content area of secondary science, though grade 6 still is elementary in terms of certification. Students may meet daily for science, since it is required each year, for the whole year. The topics are similar to those at the elementary level, except the detail is greater. Major topics include human systems, cells, genetics, reproduction, evolution, earth and celestial surroundings, erosion, rocks and minerals, earthquakes, properties of matter, chemical and physical changes, energy forms.	Science is taught by a science specialist. Students take a science course for the whole year. Courses typically are chemistry, physics, earth science (environmental science), and biology. Students meet for lecture and laboratory classes.

Table 2 Science at different grade levels

In analyzing the Tables 1 and 2 (K-12 Engineering and K-12 Science), you will notice there is very little overlap in terms of key ideas. Science is concerned with understanding the natural world, Engineering is concerned with understanding the human-made world. Comparing the strands of K-12 Engineering noted in Figure 1 with the four themes from *Taking Science to School*, there is again little in the way of connection. For instance, "understanding nature and the development of scientific knowledge" does not directly link to any of the engineering strands, it indirectly links to "making connections to M, S and SS/Hum". This is not to say that connections cannot be made, the content of *Engineering is Elementary* does just that in terms of replacing some science curriculum with engineering curriculum. However, the strength of K-12 engineering is including material related to all the strands in Figure 1, not just one or two.

Importantly, another aspect of K-12 Engineering that needs to be explored is using engineering design as a pedagogical approach. This has had success in different content areas; success being defined as improved student learning and interest in the core content (Koch and Burghardt, 2002) (Akins and Burghardt, 2006). However, there have been no rigorous studies to date.

Contrasting K-12 Engineering with College Level Engineering

There are significant differences between K-12 Engineering and College Level Engineering, differences in emphasis for the different conceptual areas. The six strands noted in Figure 1 are more equally weighted with one another in K-12 education, with the exception of the first strand dealing with creativity, which may be smaller than the rest in terms of instruction, though not necessarily importance. When we think about teaching the human-made world for all K-12 students, it is challenging to make one strand more significant than another.

However, in college the modeling strand begins to widen and the other strands become support areas. Much of the engineering curriculum is primarily devoted to analysis (modeling) and secondarily to systems and design. The other strands are of lesser curricular importance. The ABET accreditation guidelines, which drive curriculum, enforce this view. Similarly, the Professional Engineering Fundamentals examination focuses primarily on engineering analysis, so majors that find the PE license important need to assure students an education congruent with it.

Conclusions

Returning to the initial questions, engineering (the verb) provides all students with problem-solving strategies for understanding the human-made world and for applying concepts in mathematics, science and social science and humanities. Engineering (the noun) can refine these skills for students interested in further exploring the human-made world. The prime goal for K-12 engineering relates to furthering the intellectual capability of all students to understand the technologically complex world we live in and through a system (engineering) that meaningfully connects mathematics, science and social sciences and humanities. In terms of K-12 education, the habits of mind and engineering design would be part of all students' education, K-12. Thus, Engineering is the study of the human-made world.

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