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Branson Lawrence

Illinois Mathematics and Science Academy, branson@imsa.edu

Diane Hinterlong

Illinois Mathematics and Science Academy, dlh@imsa.edu

Laurie S. Sutherland

Illinois Mathematics and Science Academy, sutherla@imsa.edu

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Chapter 15

*Branson D. Lawrence, Jr., Diane L. Hinterlong,
and Laurie S. Sutherland*

Engineering Education for High- Ability Students

“The essence of engineering is creation—engineering creations serve the welfare of humanity and the needs of society. Engineering will create the future for people and society, just as it has always done in the past”—C. Daniel Mote, Jr., Ph.D., President, National Academy of Engineering, personal communication

Theoretical Rationale Concerning Teaching Adolescents and Engineering

Engineering has long been considered the field of expertise leading to the solutions of problems that have otherwise been

constrained by several parameters. Today we know that constraints can be quickly broken down within days or even within minutes.

Let us consider an example from history—of crossing a major river system—and the breakthrough feats of engineering that now serve “. . . the welfare of humanity and the needs of society” (Mote, 2013, personal communication). We have known that Native Americans crossed the Mississippi River in canoes and later by the first frontiersmen in ferries in their push to the West. To meet the needs of an increasing westward migration, the Eads Bridge was constructed in 1874. It was the world’s longest arch bridge that connected St. Louis, MO, and East St. Louis, IL.

Just 25 years before the construction of Eads Bridge, the technology for mass-producing steel, named the Bessemer process, was developed in the 1850s. The constraints of cost and availability changed—steel became inexpensive and abundant—which provided the solution needed by engineers to design a remarkable bridge, one that could carry a train over the Mississippi River.

One hundred fifty years later, with the advancement of modern technologies, the development of alloys and prestressed concrete has enabled today’s engineers to design lighter and stronger bridges. From canoes and ferries to bridges of steel, alloys, and concrete, the constraints of river crossing have yielded engineering feats.

Throughout time, engineers have responded to challenges posed by the natural and physical world, yet in today’s society the “welfare of humanity and needs of society” (Mote, 2013, personal communication) are complex and span healthcare, technology, and energy—from devices needed to assist and improve the quality of life (such as artificial limbs for amputees) to the impact of global climate change on a vast scale (such as the development of new power sources). The reality of engineering has been further intensified by the rise of a global economy and access to more and more information and data. For example, processes that once worked well for a particular industry, such as molding of plastic parts, are quickly improved upon by newer technologies, such as 3D printing, helping to create better products for the world’s citizenry.

Engineering education seldom addresses these complex, multifaceted, and challenging issues facing today’s engineers, but why? The answer is complex and is rooted in our experiences from our encounters with this field through schooling. First, engineering lacks definition for the general public, and its scope is viewed in the broadest of terms. Second, for children in elementary school, engineering is viewed in terms of construction—building small machines and structures. Third, when these students enter secondary school, they consider engineering as a high-level, mathematically dense field related to constructing bridges and spacecraft. The result? Experts feel that these limited views have led to an incomplete and inaccurate understanding of engineering and a subsequent lack of interest in post-

secondary engineering studies. And within today's field of STEM education, the "E" has yet to clearly and firmly emerge:

Engineering is a field that is critical to innovation, and exposure to engineering activities (e.g., robotics and invention competitions) can spark interest in the study of STEM or future careers (National Science Board, 2010). Exposure to engineering at the precollegiate level is currently rare (Katehi, Pearson, & Feder, 2009) and Next Generation Science Standards (NGSS) change that exposure to necessity. (National Science Teachers Association [NSTA], 2013, p. 2)

More recent curricular trends in which teachers design engineering challenges for their students, such as building electric cars, bridges, and other architectural structures, have not resulted in an overall increase of students enrolling in undergraduate engineering programs. As a matter of fact, enrollment in engineering programs has experienced a 5.6% increase relative to the 34% increase in the overall college population, yet there remains a marked lag in the enrollment of Black and Hispanic students (National Center for Education Statistics, 2011; Yoder, 2011).

Defining Engineering Talent and Habits of Mind

Engaged, active learners. Over the course of their careers, engineers command a breadth and depth of knowledge from science, mathematics, society, politics, and economics that is needed for continuously updating their knowledge of the latest discoveries and advances. Driven by curiosity and enabled by rapid information technology, engineers are kept abreast of the latest advancements almost instantaneously. Today's scientific knowledge is fluid and complex, yet these traits of engineering remain constant: the ability to define structure, plan, repeatedly evaluate, and align results to the initial objective. Engineering teachers need to facilitate their students' ability to access information effectively and to apply it appropriately, as well as to foster a strong foundation in science and mathematics. Skill development in creativity, communication, and business acumen is the hallmark of an effective engineering education program and curriculum.

Creativity. The foundation of engineering is creativity. Scientific and technological discoveries happen rapidly, requiring engineers to synthesize data and to apply techniques from seemingly divergent and interdisciplinary sources. For example, mechanical engineers who traditionally think in terms of metal systems will also need to consider the interplay and application of biological and nanoparticle systems.

Effective engineering programs for talented secondary students provide opportunities to grapple with real-world problems that require creative solutions and innovations. Their teachers design learning scaffolds that support breakthrough thinking and collaboration through problem-centered lessons in which opportunities to propose solutions to current, relevant, and engaging problems are explored from all directions. See Table 15.1 for a sample case study of a scaffolded project.

Communication. Engineering requires effective skills in speaking, writing, and listening. Educators can nurture their students' communication skills by designing team engagement and discourse around engineering problems that require the application of technological, mathematical, and scientific skills and knowledge, as well as experiences with diversity and opportunities for practicing presentations, public speaking, and technical writing. The designs of tomorrow's talented engineers will successfully find their way into the world if interactions and communications with partners, clients, and stakeholders are effective. Developing emotional intelligence and communication skills can begin in the secondary classroom so that future engineers are ready to meet the technical challenges of the profession, as well as the variety and diversity of our world.

Business acumen. Engineers possess analytical and technical skills, deep content expertise, creativity, effective communication, and leadership skills. They are broadly educated global citizens who, while serving to advance the human condition, often find themselves navigating the pressures and challenges that are related to working with commerce, business, and the public. Technology has fueled the economic engine for individuals, companies, government, and social enterprise; therefore, an engineer's ability to determine economic advantages and opportunities for designing products and systems depends on and is related to his or her business acumen. It is important for well-rounded engineering education programs to provide opportunities for talented secondary students to develop an awareness of business, and this can be achieved through developing business plans, constructing cost analyses, exploring market trends, and implementing effective marketing or promotional strategies.

STEM: The Distinctiveness of Engineering Education

Historically, it has been assumed that the content taught in mathematics and science is sufficient for developing engineering skills. In response to the shortage of qualified engineers in the United States, this assumption has been scrutinized and revised. Today, it is understood that the skills for developing a scientist or scientific thinker are similar, *but not congruent* to the skills necessary for developing an engineer (Bybee, 2011). Table 15.2 illustrates the ways the two areas are similar as well as slightly different.

Table 15.1
Case Study 1: Fuel Efficiency

A university engineering department proposed a fuel efficiency contest. Students were to design a car to compete on a course and the most efficient car, in terms of best miles per gallon of fuel, would win. Several groups completed the project successfully; however, one group approached the problem differently: The students designed a car that ran on air.

How did they do it? These students designed their pneumatic car by compressing air into a tank and allowing its potential energy to drive the pistons in the cylinders.

What can be learned from this group of engineering undergraduates? As educators, we realize that “thinking outside the normal parameters” is a difficult skill to impart to our students who have been schooled to arrive at one correct answer for each assigned problem. This runs counter to the type of thinking that engineers actually do.

How does this apply to talented engineering students in secondary education?

This creative process can be nurtured through learning experiences in which students apply a combination of divergent and convergent thinking in the context of well-designed problem-centered learning experiences. Initially, divergent thinking about an assigned problem is employed; once a perceived best solution is agreed upon, convergent thinking is then applied.

Students need encouragement to articulate their ideas in a classroom environment that supports expression and exploration of new ideas; that gives and receives constructive critique and provides some “rules of the road.” In a well-designed problem-centered learning experience, problems can have multiple correct answers; students may need to seek additional information as they work through the problem; the best solution is likely to be found through the exploration of multiple possibilities; novel ideas may prove to be the best; and the pursuit of an idea that does *not* work is *not* failure.

Table 15.2
Comparison of Science and Engineering

Science	Engineering
Science begins with a question about particular phenomena (e.g., “What particles make up matter?”).	Engineering begins with a problem that needs to be solved (e.g., “How can we detect a particle?”).
Science uses models to construct explanations.	Engineering builds models to construct solutions.
Science data are used to support or disprove a hypothesis.	Engineering data are used to improve or change a system or product.

In this comparison, a distinctive relationship emerges between the “S” and “E” of these STEM fields, which serves as the basis for the development of engineering programs for secondary students that feature differentiated learning activ-

ities, assignments, projects, and assessments—with a focus on the distinctiveness of engineering skills and ways of thinking and doing.

Integration Within and Beyond the STEM Framework

The cognitive activities used by engineers and engineering students utilize higher order thinking skills. These professionals study problems, research appropriate content, analyze proper solutions, and assess their success. For secondary students, the study of engineering also leads to higher levels of course content acquisition in science and mathematics. The case study in Table 15.3 illustrates this use of higher order thinking skills.

Through experiencing the iterative nature of engineering, students learn that science and mathematics are organic—these subjects become unbound from rote learning. As engineering teachers develop curriculum, it is essential that a reflective component be included. For instance, when engineering students work through an engineering problem—designing, building, and testing models—the reflective practice of reviewing it and making project improvements becomes a critical component of the lesson and the process of changing parts, systems, or production procedures; in all, the real work of engineers.

This reiterative process seldom occurs in science classes. Typically students complete lab reports and submit them to the teacher for grading. Similarly, in mathematics classes, students take quizzes and see their answers marked as correct, partially correct, or incorrect. In contrast, in most construction competition lessons, such as bridge building, students receive only a small allotment of material and have one chance to build the bridge that holds the most weight. Lessons like this need to incorporate technologies, such as sensors and videos, creating an opportunity for students to analyze their work. They should be able to understand which concepts worked well and identify those that need improvement.

Engineering learning experiences need to be communicated in writing and shared through presentations so that students become engaged in the active transfer of new knowledge to their teachers, peers, and other interested individuals. Assessment of engineering lessons must include a review of these critical communication skills for the project as a whole to be considered successful.

Review of Current Empirical Literature

The body of empirical literature for engineering education that is specifically focused on high-ability secondary students is small, yet emerging. The topics for

Table 15.3
Case Study 2: Energy Production

Talented secondary students were introduced to a problem in their engineering class that involved energy production for a hydroelectric dam.

What was needed for the engineering problem? The complex integration of science and mathematics required students' understanding that the potential energy stored behind the dam could be converted into kinetic energy by moving the water from a high gravitational position to a lower gravitational position through the application of proper physics and mathematical equations. By varying certain parameters of the system, as engineers are apt to do, energy production could be improved.

What was gained? By changing each variable and developing sets of equations, engineering students experienced the interrelationships of mathematics and science and achieved success in problem solving.

secondary, talented engineering students are similar to those reported in higher education regarding the education of undergraduate engineering students: curriculum and instruction (de los Ríos, Cazorla, Díaz-Puente, & Yagüe, 2010); the learning styles of engineering students (Felder & Brent, 2005); fostering skills in creativity (Cropley & Cropley, 2000; Felder, 1988; Petty, 1983); collaboration and innovation (Koszalka, 2010; Kotru, 2010); and problem framing (Sunthonkanokpong, 2011). The literature for engineering secondary education of high-ability students includes topics ranging from policy work to developing diverse talent. The National Association for Gifted Children's (NAGC) report, *Science, Technology, Engineering, and Mathematics: Our Nation's Renewable Resources* (as cited in Jolly, 2009) states that, "current STEM initiatives provide an opportunity for gifted education to inform the practices and curricula required of rigorous and high-level coursework, while gifted students also can benefit from access to such high-level course work" (p. 52).

The question emerges: Is the small body of literature because of a lack of engineering experiences for talented secondary students? Actually it is not a lack, but an emerging curricular and pedagogical field that indicates a need for improving engineering K–12 education overall, with a focus on STEM education to be reconsidered as a more integrated whole (Katehi, 2009). Consider the following description:

The teaching of engineering in elementary and secondary schools is still very much a work in progress. Not only have no learning standards been developed, but also little is available in the way of guidance for teacher professional development, and no national or state level assessments of student accomplishment have been developed. In addition, no single organization or central clearinghouse collects information on K–12 engineering education. (Katehi, 2009, p. 2)

The National Science Board (2007) described the importance of engaging interest in engineering education of girls and minorities beginning in grades 4–6 and stimulating interest in K–12 mathematics and science through greater exposure to engineering in K–12 education as follows: “There should be a K–12 engineering curriculum standard to complement, enhance, and enrich the curriculum in math and science” (p. 16). Developing STEM talent must start early and must include diversity and a wide range of STEM interests (Roberts, 2010b). Yet discovering and developing diverse STEM talent, especially in academically talented urban youth, is critical (Marshall, 2011).

Mativo and Park (2012) delineated K–12 engineering from collegiate engineering education and also from science and mathematics by identifying five benefits of K–12 engineering education:

1. It cultivates learning and accomplishment in science and math.
2. It allows enhanced comprehension of engineering and engineers’ work.
3. It increases knowledge and ability in engineering design.
4. It provides career interest in the engineering field.
5. It strengthens technological literacy. (p. 26)

From summer and Saturday learning experiences to talent development in specialized STEM schools, diverse STEM learners must include students from diverse rural and urban areas, ethnic and racial groups, all economic levels, and those identified as twice-exceptional and non-native speakers of English (Roberts, 2010a).

Few studies exist that describe the identification and recruitment of students talented in mathematics and science for secondary engineering programs (Chan et al., 2010). However, in engineering-related fields, talent is not only science and mathematics is needed, but “communications, literacy, teamwork, and leadership talents are also critical to the success of engineering design projects” (Mann, 2011, p. 639). These strengths include the need for high levels of creativity, better innovation, and the ability to make novel inventions and are illustrated in a “Hypothetical Engineering Creativity Enterprise Diagram” (Badran, 2007), which features a matrix that includes engineering creativity, technical creativity, and innovation for undergraduate engineering programs (p. 579).

Although the need for further study of the impact of STEM schools on the gifted education community and beyond is clearly understood (Subotnik, Tai, Rickoff, & Almarode, 2010), there are no studies specifically reporting the impact that engineering curriculum for talented students has on this population of secondary students. Mann (2011) identified engineering as a talent domain and a curriculum area to be developed:

Engineering is a linking subject that can connect with other fields while engaging students in learning activities . . . Integrating engineering concepts and using correct terminology, using appropriate teaching strategies to demonstrate these concepts in context, and providing engineering design experiences to students will increase the awareness of engineering.” (p. 652)

Bybee (2011) identified the relationship between science and engineering practices as “complementarity” and suggests they be considered as both learning outcomes and instructional strategies:

They represent both educational ends and instructional means. First, students should develop the abilities described in the practices, and they should understand how science knowledge and engineering products develop as a result of the practices. Second, as instructional strategies, the practices provide a means to the learning outcomes just described and other valued outcomes, such as students’ understanding of the core ideas and crosscutting concepts expressed in the framework. (para. 6)

Mativo and Park (2012) explained that the ability to make connections, generate innovative ideas, and creatively solve real-world problems “are all necessary for the development of engineering thinking and are tenets of curriculum development in gifted education” (p. 28). They urged preservice programs for future K–12 engineering teachers to focus on how scientific, technical, and mathematical concepts integrate and support problem-solving skills required of engineers.

Alignment With STEM, Common Core State Standards, Content Standards, and 21st-Century Skills

Founders of Franklin W. Olin’s College of Engineering defined an engineer as “a person who envisions what has never been and does whatever it takes to make it happen” (National Research Council, 2013b, p. 1). Engineering students need to be involved in solving real-world problems. It is through the process of engineering that the content of various disciplines is integrated to achieve a desired outcome or goal. Likewise, the goal of education in engineering needs to encompass this integration of concepts and be focused on solving real-world problems. Engineering education provides a remarkable opportunity and educational framework for the integration of mathematics, science, and technology.

Engineering Standards for K–12 Curriculum

The integrated nature of engineering as a discipline supports the attainment of a multitude of standards through a well-designed curriculum. *Engineering standards do not currently exist for K–12 curriculum.* However, thoughtful design of curriculum can readily address the English and Language Arts Common Core State Standards (CCSS), Next Generation Science Standards (NGSS), and 21st-century skills. A pedagogical approach employing an engineering design process to identify and solve problems can provide the foundation for a meaningful K–12 engineering curriculum. This approach keeps the student at the center of learning and places problems in context. It not only supports attainment of standards, but it requires creativity, communication, and the ability to view problems from multiple perspectives and explore multiple solutions.

A Framework for K–12 Science Education

Utilization of an engineering design process approach to curriculum aligns with the engineering practices as outlined in *A Framework for K–12 Science Education* (National Research Council, 2013a). First and foremost, the process starts with the identification of a problem. Next, students must engage in a process of planning to solve the problem. This stage may involve the use of models along with analyzing and interpreting data produced through initial investigations. Depending on the nature of the problem, mathematical and computational thinking may play a significant role in the process. Using information gathered along the way, students propose and evaluate problems. This entire process is cyclical in nature and may require several iterations. In the evaluation of solutions, students need to communicate the effectiveness and shortcomings of proposed solutions with arguments clearly supported by evidence.

The Framework for 21st Century Learning

The Framework for 21st Century Learning articulates skills, knowledge, and expertise in which students must become proficient to succeed in work and life. Specifically, the framework references essential skills for success in today's world, such as critical thinking, problem solving, communication, and collaboration (The Partnership for 21st Century Skills, n.d.). Once again, an engineering design approach to pedagogy effectively aligns with outcomes identified in this framework. While seeking solutions to problems, students must learn to think creatively and work effectively with others in the process. They need to view the problem, as well as potential solutions, from multiple perspectives. In the process, the individual strengths that each student brings to a group project become critical. In a school setting, it may not be reasonable to test multiple solutions

because of time and acquisition of resources. Therefore, it is essential that students work collaboratively to assess the potential success and shortcomings of multiple approaches in advance of physically constructing a solution. In order to achieve the greatest success in this process, students must be able to communicate their ideas effectively, ask questions, seek feedback, and make adjustments to their thinking based on input from others.

Mathematics Standards

In addition to mathematics content, the Common Core State Standards for Mathematics (National Governors Association Center for Best Practices & Council of Chief State School Officers [NGA & CCSSO], 2010b) articulate Standards for Mathematical Practice. Although students may engage with mathematical content aligned with the CCSS through an engineering design process, they are almost guaranteed to meet some of the standards for mathematical practice. First and foremost, students who are proficient in mathematics, as well as in engineering design, must make sense of a problem and look for a variety of pathways to its solution. In some cases, they may need to develop mathematical models to better understand the problem and its potential solutions. As students work to develop solutions, they must state assumptions, make conjectures, analyze situations, and communicate arguments to their peers. In addition, they must use the same processes to critique the reasoning of others. This process is important in both the development stage and the reflection stage of the engineering design process. Finally, students need to carefully select appropriate tools as they evaluate their designs.

English Language Arts Standards

Secondary students can effectively meet many of the CCSS for English language arts (NGA & CCSSO, 2010a) through the written and oral communication skills that are essential elements of the engineering design process: communicating initial plans, offering feedback to others, and providing explanations of processes as well as potential solutions to engineering problems. Also, while in the process of designing a solution, students must synthesize and integrate relevant information following the undertaking of applicable research. The case study in Table 15.4 demonstrates how an engineering curriculum meets multiple standards.

Table 15.4
Case Study 3: Meeting Multiple Standards

<p>A project used by teachers in a STEM high school for gifted students features an engineering curriculum that illustrates the capacity of the engineering design process to meet multiple standards through a relatively simple problem.</p>	
<p><i>What is the project?</i> On the first day of class, students are challenged with the task of designing a cardboard boat to support a team member inside the boat for a race across the school pool. They are limited by time and allotments of cardboard and duct tape.</p>	
<p><i>How is learning assessed?</i> Students are required to submit a written reflection of their design when the event is completed. It is especially important that the reflection demonstrate how students applied their knowledge of mathematics and physics to explain the successes and failures of their particular design. The following rubric demonstrates the alignment of standards with the process of meeting this engineering challenge:</p>	

What Floats Your Boat? Building a Cardboard Boat

	Next Generation Science Standards	21st-Century Skills	Common Core State Standards in Mathematics	Common Core State Standards in English Language Arts
Assigning the Task	Defining the problem	Collaboration for developing effective team; brainstorming	Make sense of problems and persevere in solving them	Careful reading of rules and regulations
Exploring Solutions	Use of models, mathematics, designing solutions	Problem solving and making judgments; critical thinking; creativity; collaboration	Model with mathematics; construct viable arguments; critique the reasoning of others	
Testing Product	Gathering data; collecting evidence	Collaboration	Strategic use of appropriate tools	Clear and coherent writing; discipline-specific argument
Reflection	Analysis and interpretation of data; use of evidence to support effectiveness; use of mathematics in analysis of product; evaluation and communication of information	Assess productivity and collaboration; clear articulation of process and effective communication	Construction of viable arguments; critique of the reasoning of others	

Challenging Curriculum: Middle School and High School

Currently, engineering is a STEM curricular outlier. Until the release of more recent versions of science and mathematics standards, there has not necessarily been a direct connection between the science and mathematics content emphasized in schools and items placed on standardized tests. As noted previously in this chapter, the new standards require shifts in curriculum focused on developing the habits of mind of engineers: creativity, communication, and developing systems and products that have real-world application. This necessary shift has been reinforced by greater business and school collaborations and partnerships. These schools develop and use curriculum that is created through a unique and intentional collaboration among middle school, high school, postsecondary, corporate, governmental research, and nonprofit partners. This collaboration supports the development of effective and efficient strategies to strengthen STEM education and build students' academic skills in these critical subjects.

Engineering Education Programs for Students: Gifted, Talented, Motivated, and High Achieving

The schools in Table 15.5 feature a variety of engineering education programs—ranging from multicourse engineering sequences to introductory semester courses, electives, summer camps, and/or partnership programs with colleges and universities. Many are members of The National Consortium of Specialized Secondary Schools in Mathematics, Science and Technology (NCSSSMST). Engineering education for gifted students should follow the basic rules of teaching and learning in general. However, for gifted students a curriculum demanding more connections among STEM areas should be expected. The “Wind Energy Project” (see Table 15.6) is an example of a unit that encourages talented secondary students to connect mathematical properties, scientific laws, and engineering.

In this unit, talented engineering students use modern technology, such as computers, tablets, or even smartphones with relatively inexpensive sensors, software, or applications to periodically test their work for design improvements. Figure 15.1 shows a typical sensor and corresponding output on an iPad. The culminating learning experience for the Wind Energy Project involves students conducting tests in 5-minute intervals and recording results to make final adjustments in order to optimize their designs. This final adjustment period is con-

Table 15.5
Educational Institutions for High-Ability Learners
Offering Engineering Experiences

Alabama	Alabama School of Mathematics and Science
Arkansas	Arkansas School for Mathematics, Sciences and Arts
California	California Academy of Mathematics and Science
Colorado	Center for Bright Kids Regional Talent Center (formerly the Rocky Mountain Talent Search)
Delaware	Charter School of Wilmington
Georgia	Rockdale Magnet School for Science and Technology; The Center for Advanced Studies at Wheeler Magnet School; Gwinnet School of Mathematics, Science, and Technology
Illinois	Illinois Mathematics and Science Academy; University of Illinois Laboratory High School; Center for Talent Development at Northwestern University
Indiana	The Indiana Academy for Science, Mathematics, and Humanities
Iowa	National Scholars Institute, University of Iowa Belin-Blank Center for Gifted Education
Kentucky	Gatton Academy of Mathematics and Science
Louisiana	Louisiana School for Math, Science, and the Arts; Patrick F. Taylor Science and Technology Academy
Maryland	Baltimore Polytechnic Institute; Blair Science, Mathematics, Computer Science Magnet; Eleanor Roosevelt High School; Johns Hopkins Center for Talented Youth; Poolesville High School Magnet Program; Science and Mathematics Academy at Aberdeen High School
Massachusetts	Massachusetts Academy of Mathematics and Science
Mississippi	Mississippi School for Mathematics and Science
Missouri	Missouri Academy of Science, Mathematics and Computing
New Jersey	High Technology High School of New Jersey; Bergen Academies, The Academy for the Engineering and Design Technology; Marine Academy of Science and Technology; Red Bank High School, Academy of Engineering
New York	Bronx High School of Science; Clarkson University Early College Program; The High School of Math, Science and Engineering at the City College; Stuyvesant High School
North Carolina	North Carolina School of Science and Mathematics; Duke Talent Identification Program
Ohio	Hathaway Brown, Kettering Invention Lab and Engineering Academies

Table 15.5, continued

Pennsylvania	Downington STEM Academy
South Carolina	South Carolina Governor's Schools for Science and Mathematics
Texas	School of Science and Engineering Magnet; TAG Magnet School for the Talented and Gifted; Texas Academy of Mathematics and Science
Utah	Academy for Math, Engineering and Science
Virginia	Central Virginia Governor's School for Science and Technology; The Governor's School for Science and Technology; Roanoke Valley Governor's School for Science and Technology; Shenandoah Valley Governor's School; Thomas Jefferson High School for Science and Technology

Note. The above list is not comprehensive.

Table 15.6
Case Study 4: Wind Energy

<p>The curricular unit associated with this project introduces students to the basic premise that electrical energy can be generated by harnessing natural air flow around the planet.</p>
<p><i>What is the project?</i> Students design a wind generator from basic materials: wooden sticks, paper, and an electric motor. For middle school students, this lesson might conclude with measuring the output voltage of each group's apparatus. High school students should make many more connections to mathematics and science.</p>
<p><i>What are the science applications?</i> An initial discussion would lead students to consider which factors and variables would make a wind generator more efficient. They are then asked to make a list of relevant variables and devise a list, which would likely include mass, inertia, area swept by the blades, density of air, speed of air, friction, and angle of attack. These are concepts studied in other science courses, and students will need to research these concepts as they become relevant in the project.</p>
<p><i>What are the mathematical applications?</i> It is important for students to understand the mathematical relationship among variables and work with their team to set up equations that would predict the theoretical production of power. Typically, students predict that wind speed and the area swept by the blades are directly proportional to power and that friction or the moment of inertia is inversely proportional to power.</p>
<p><i>How are connections made?</i> Scientific and mathematical relationships are tested on a simple apparatus that allows for variable blade lengths, masses, and wind speed. Students collect data to determine that some variables, such as wind speed, have a much greater effect on power; doubling the air velocity yields eight times the power, whereas the area swept by the blades is a simple 1:1 ratio. Gifted secondary students with strong mathematics and science skills work the variables through different iterations to propose the most efficient solution.</p>

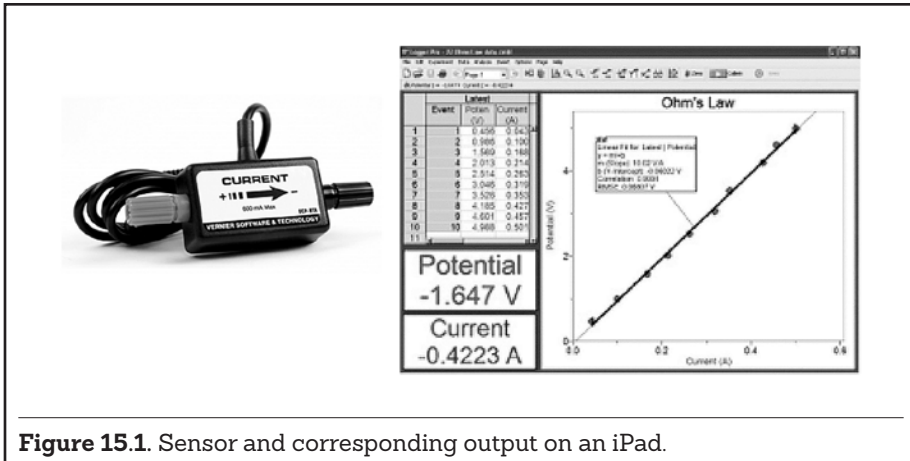


Figure 15.1. Sensor and corresponding output on an iPad.

ducted during a set time of 20–30 minutes. The group that has the largest area under the curve of the power versus time graph for a 5-minute interval is deemed the winner. All students submit their best attempt accompanied by the calculation of the integral from their data.

Illinois Mathematics and Science Academy

Since 2006, engineering has been taught as a credit-bearing course at the Illinois Mathematics and Science Academy (IMSA) and is based upon projects similar to the Wind Energy Project. Each project's curricular design incorporates mathematical reasoning, scientific inquiry, and group dynamics. IMSA students complete design processes for several projects: cardboard boats, robots, computer science, and airplanes. Once exposed to these projects' focused problems, students are given a broad question to think about and are encouraged to discuss how they can solve it through engineering principles.

Project-based learning. The final project for this course is open-ended from the concept through the design phase, culminating in the final product. Students are given a thoughtful and challenging design statement: "Devise a product or a process that advances the human condition." Increased student motivation results from the opportunity for students to follow their own passion through a challenging yet flexible project incorporating such autonomy. "Project-based learning is a comprehensive approach to classroom teaching and learning that is designed to engage students in investigations of authentic problems" (Blumenfeld, 1991, p. 1).

The final project design for the engineering class at the Illinois Mathematics and Science Academy begins with each student presenting an innovative idea followed by "What If" critiques from the class. For example, a student might suggest a design for a hydroelectric generator (see Table 15.7) and classmates would ask,

Table 15.7
Case Study 5: “Rolling” Water

What is the “authentic problem”? IMSA students learned that one of the barriers to education facing girls and women in African villages is the need to transport water twice a day by foot from over a mile away. Most girls could carry one to two gallons of water per trip in jugs balanced on their heads. Neither strapping mechanisms nor wheelbarrows had increased the amount of water transported.

How was the problem approached? One student suggested using a device like the lawn roller—utilizing a cylindrical drum filled with water and pushed by using side-handles. Further research showed this invention was developed yet cost prohibitive for the villagers. Determined, the students applied their technology skills in CAD and 3D printing for a design that could be nested in a container smaller than a 5-gallon bucket (thus greatly reducing material and shipping costs) and then assembled onsite with PVC glue. The roller could carry 20 gallons of water per trip.

A prototype was constructed and presented to the class, teachers, and a panel of local engineers. The students received feedback, then met with a business/entrepreneurial group on campus and developed a business plan and sales pitch for their product. Following several modifications, their invention was ready to be entered in a design competition. It was a winner and with the help of a school advisor, they pitched their product to several not-for-profit organizations and it was eventually sold.

What was learned? Although every project initiated by talented secondary students in an engineering class does not reach this final outcome, the possibility exists. The high level of engagement fostered through this process results in a clear ownership of learning on behalf of the students. They are willing to challenge themselves, take risks, seek feedback, and make adjustments to their designs because they are genuinely impassioned about their work. Students set high expectations for themselves and have the opportunity to experience both the successes and failures inherent in the engineering design process.

“*What if it were turned 90 degrees?*”, “*What if it were suspended on superconducting magnets?*”, “*What if it were placed in the Gulf Stream rather than at a dam?*” After all ideas are shared, several projects are selected to progress beyond the idea stage. Students elect a group project that they are interested in advancing and each group spends the rest of the term designing and building a working prototype of the project. Finally, all projects are presented as a team in the form of a final presentation that is conducted as a sales pitch to the class, the instructor, and practicing engineers who are invited guests from the community.

Strategies Used to Impart Curriculum: Middle and High School

As stated earlier, engineering education of gifted students needs to be centered on the process of studying a problem, looking at it from all angles, proposing many solutions, and testing and refining the solutions. Programs designed to achieve these goals can be offered through regular classes, afterschool programs, or extracurricular activities. The experiences in these programs should enable students to pursue solutions to challenging problems and ask their own compelling questions connected to real-world problems. In this process, students learn to collaborate with each other and with students and experts from around the world using modern communication technology, such as blog posts and video conferencing.

Engaging students from diverse backgrounds and interests is challenging for engineering teachers, but one successful topic strategy involves nearly all students' universal concern for the natural environment. Many find environmental challenges to be personally compelling and will join engineering and research teams to tackle energy issues, and subsequently will learn new academic content along the way.

Personalization. Students are at the center of their own learning in the engineering design process, and personalization of learning is a natural outcome. Knowledge acquisition is attained through collaborations with peers, teachers, and experts in the field. Educators of gifted students might find it challenging to design engineering curriculum that facilitates interest within the construct of cooperative learning environments while still meeting content goals.

Addressing this challenge may be accomplished through very different pathways—a convergent pathway or a divergent pathway. Many popular programs for engineering education in middle and high schools are focused on convergent pathways and begin with a broad overview course focused on helping students understand engineering through activities and projects. Options to explore more specific areas, such as biomedical sciences, exist for students as a follow-up to the introductory engineering course.

Other engineering programs for talented secondary students follow a more divergent pathway. At IMSA, engineering has several focused projects that address the qualities of an engineer and then broaden the scope for students to be able to solve problems and pursue solutions to questions that are of particular interest to them. This supports greater personalization and higher levels of student motivation by allowing students to have more control over their learning.

Project-based learning. There are seemingly endless options for projects geared toward introducing students to engineering. For example, a group of secondary engineering students visited an industrial robotics lab at a local university,

where they learned to program small robots on a mock assembly line. The following week they returned to class and were provided with tubing, large syringes, strips of wood, wire, 6V batteries, and hinges. They were given a design challenge: to build a robotic arm that could lift ping-pong balls from a bowl and place them in a tray. They worked in teams, reviewing and learning new concepts: mechanical advantage, hydraulics, pneumatics, electricity, and magnetism. Another group of students built small programmable robots from purchased kits. Both of these projects were tested through competition and assessed through the journal entries submitted by each individual student. These projects enhanced learning by allowing the students to build upon the demonstrations they observed at the university.

After the completion of several focused projects, students are prepared to engage in more open-ended projects, such as the wind energy project. In either approach, the engineering cycle started with a problem or question followed by design, testing, evaluation, and revision that encourages deeper thinking about what scientific concepts are necessary for an entire system to function properly.

Regardless of the approach taken to designing an engineering task, it is critical to incorporate creative problem solving as well as testing, analysis, feedback, reflection, and revision. In the focused projects previously described, students learned that there was not a single correct answer. Although they were tackling the same problem, the approaches used to solve the problem were unique and supported the creative nature of engineering. The team approach allows for the consideration of multiple perspectives in viewing both the problem and the solution. Finally, communication—both during the course of a project and at its end—is also a key element.

Appropriate Assessment

This chapter has examined the need for teaching talented secondary students the essential skills necessary for successful engineering—creativity, communication, business acumen, and the integration of mathematical reasoning and scientific inquiry. These concepts and skills are not easily evaluated through traditional testing, and it is imperative and appropriate that a variety of assessments be implemented to determine the depth of learning for these engineering traits.

Self-evaluation and peer evaluation. First and foremost, engineering is a group activity. It is necessary for students to share their ideas, discuss methods, and divide the tasks of construction and planning. It is challenging to identify individual work and contributions when assessing group projects; however, one method that has been used successfully is to combine self-evaluation and peer evaluation. This type of formative assessment aligns well with Bloom's (1956) taxonomy of learning domains, and an example is provided in Figure 15.2. It

Project Name: _____
Names of Group Members: _____
What was accomplished?
What problems did you overcome?
What is your plan?
What needs to be procured (with picture)?

Figure 15.3. Form 2: Engineering journal progress report.

Summative assessment. The summative assessment of each engineering lesson should allow students to mentally reconstruct the process and the justification of the plan. In addition, scientific and mathematical concepts applicable to the process should be incorporated into the assessment. Students should also be able to analyze their work in light of repetitive testing and demonstrate their ability to gather data, make changes, and re-evaluate their hypothesis. Furthermore, they should be able to explain what worked well and what needed rethinking by using their results and the mathematical and scientific concepts related to the problem.

Often the difficulties faced by students in their work are not related to the basic science of the project. For example, difficulties may be a result of an electrical malfunction, such as a motor overheating and becoming shorted. These unforeseen problems that arise are part of engineering, and students need to be able to analyze the situation and decide next best steps.

Although the educational goal for engineering teachers of talented secondary students is concept mastery and understanding the engineering process, the ultimate goal for engineers is to develop a product that works. Therefore, an assessment component is needed to evaluate the final product with respect to its functionality. The goal of the project needs to be clearly stated at the beginning of the unit and success needs to be defined meticulously. The example from the wind energy project illustrated in Figure 15.4 clearly states the end result as the energy generated over the 5-minute period. This is a small, yet significant part, of the student's grade. For example, successful completion may be worth a total of 10% of the grade based on 10/100 points for the entire project. The group producing the greatest energy output would receive 10 points, the group with the second greatest output would receive 9 points, and so forth, with groups earning a 10-point

Engineering Journal Entry: Wind Project	
Name: _____	
Partners: _____	
Date: _____	
Did your windmill generate electricity? Oftentimes, engineering ventures can be failures, but we can learn a great deal from both our successes and our failures.	
Picture of completed wind generator and team.	
Calculate the theoretical maximum power output of your windmill. Contrast that with your maximum measured value.	$P = C_p^{.5} \rho A v^3$ (power = square root of performance coefficient \times air density \times swept area of blades \times velocity of wind cubed) $P_{meas} = (V \cdot I)_{max}$
From your best 5-minute data set, create a P vs. t graph (in W & s) and find the total output energy (area) (in J). Report the energy in kWhr as well.	Graph P vs T Integral = _____
Force diagram of turbine blade, including gravity, force of wind, drag, thrust.	
How did you use the science and math concepts above to guide your design?	
What was the strongest aspect of your generator design? What supports your thinking that this was the strongest aspect?	
Identify one or two weaknesses in your design. How could you redesign your generator to overcome these weaknesses? Be specific.	
Clearly describe your personal contribution to your group's generator.	

Figure 15.4. Form 3: Summative evaluation.

deduction on their project for designs that did not work. This emphasizes that the engineer needs to complete tasks successfully.

Engineering projects, by their very nature, must be completed by an internal group and presented to external groups. This broader type of assessment can be completed for one large and final project. Engineers and business people from the community may be invited to watch group presentations, which allow the

students to demonstrate their creativity, communication, entrepreneurship skills, and to receive feedback from a diverse audience.

Questions for Discussion

1. Depending on the nature of the engineering project, sometimes financial constraints can restrict possibilities. What needs to be explored when resources are limited?
2. In the chapter, some suggestions were provided for evaluating individual accountability to group projects. What other alternatives might be considered?
3. Currently there is a lack of gender and ethnic diversity in engineering programs. How can this be improved?
4. Programs in most schools today separate each of the STEM fields into separate programs. What advantages/disadvantages exist in creating more integrated and interconnected STEM programs? How could this be achieved?
5. Engineering educators in middle schools and secondary schools are clearly an exception. What types of professional development programs are needed to support teachers in the successful implementation of an engineering curriculum?

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