TEACHING engineering habits of mind IN TECHNOLOGY EDUCATION

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"Engineering habits of mind are meant to help prepare secondary students for postsecondary success in engineering, whether in college or in their future careers.

With a new emphasis on the inclusion of engineering content and practices in technology education, attention has focused on what engineering content should be taught and assessed in technology education. The National Academy of Engineering (2010) proposed three general principles for K-12 engineering education in *Standards for K-12 Engineering Education?*:

1. Emphasize engineering design.
2. Incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills.
3. Promote engineering habits of mind.

Principle 3, engineering habits of mind, was proposed as an essential skill to separate how engineers think and act from ways that academic content teachers think and act. Based on this construct, this article will examine what engineering habits of mind are, explore linkages to national standards (Table 1), and propose how these habits of mind can be taught in technology education classrooms at the secondary and preservice teacher education levels.

The National Academy of Engineering (2010) describes six engineering habits of mind that include systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations. Three of these—systems thinking, effective teamwork, and concern for societal and environmental impacts of technology—were further subdivided by grade levels (K-5, 5-8, and 9-12), with examples and topics to be covered at those specific grade levels. Before addressing lesson plan ideas for the different habits, it is important to understand what the habits of mind are and any connections they may have to other national content standards.

The *Framework for 21st Century Learning* (Partnership for 21st Century Skills, 2013) envisions student success in the global world through the mastery of skills, knowledge, and expertise needed for success in life and careers. The four main outcomes called for are: life and career skills; information, media, and technology skills; core subjects; and learning and innovation skills. With the exception of ethics, there are direct links between these learning and innovation skills and the engineering habits of mind. The learning and innovation skills include critical thinking, communication, collaboration, and creativity.

SYSTEMS THINKING

In engineering, systems thinking refers to individual understanding that all technologies are interconnected. Technology is more than just an artifact or physical object. Technology includes the design and development, processes to create, and the consequences of the development, both good and bad. In *Standards for K-12 Engineering Education?* (2010), systems thinking is referred to as "a way of approaching problems with a recognition that all technologies are systems of interacting parts that are, in turn, embedded in larger systems" (p. 140). The described systems thinking is very similar to

Table 1: **Cross Matrix of *Engineering Habits of Mind*, *Framework for 21st Century Learning*, *Standards for Technological Literacy*, *Advancing Excellence in Technological Literacy*, and *Next Generation Science Standards*.**

Standards for K-12 *Engineering Education?: Habits of Mind*	*Framework for 21st Century Learning:* Learning and Innovation	*Standards for Technological Literacy* and *Advancing Excellence in Technological Literacy*	*Next Generation Science Standards*: Engineering Design
P3 (1) Systems Thinking Standard 7	Critical Thinking	*STL* 2 – Core Concepts: N, P, W, X, Y	HS-ETS1-2, HS-ETS1-4
P3 (2) Creativity	Creativity	*STL* 1 – Scope of Technology: G, H *STL* 9 – Engineering Design: J	
P3 (3) Optimism	Critical Thinking	*AETL* Assessment Standard 4c	
P3 (4) Collaboration Standard 8	Collaboration	*AETL* Program Standard 4a	
P3 (5) Communication	Communication	*STL* 8 – Attributes of Design: H	Practice 8 – Obtaining, Evaluating, and Communicating Information
P3 (6) Attention to Ethics Standard 9	Critical Thinking	*STL* 4 – Effects of Technology E, F, H, I, J *STL* 5 – Effects on Environment #H, J, L	MS-ETS1-1, HS-ETS1-3

ideas presented in Standard 2, Core Concepts of Technology, in *Standards for Technological Literacy: Content for the Study of Technology* (ITEA/ITEEA, 2000/2002/2007). The first core concept addressed in Standard 2 is Systems. The first three benchmarks at the 9-12 grade levels (W, X, and Y) are about systems thinking. For example, Benchmark 2X is: “Systems, which are the building blocks of technology, are embedded within larger technological, social, and environmental systems” (p. 42). In *Next Generation Science Standards* (NCSS Lead States, 2013a), systems and systems modeling are found at both the middle and high school level engineering standards as crosscutting concepts. Lammi and Becker (2013) report that high school students can become capable of systems thinking through the use of engineering design challenges. Examples of engineering design challenges include product life cycles, inputs-processes-outputs-feedback systems, and control mechanisms

CREATIVITY

Creativity implies imagination in the design process of engineering. Bevins, Carter, Jones, Moye, and Ritz (2012) discuss this as a role of innovation in students’ thinking about design, modeling, production, and evaluation of artifacts. Lasky and Yoon (2011) report that hands-on engineering design lessons are ideal contexts for teaching creativity to all students. Teachers can nurture creativity in two ways: using digital multimedia tools as a teaching strategy and making space for creativity in the class. This might include providing more time for brainstorming and allowing classroom space for communicating new ideas and designs. Creativity can be included in technology education classrooms through the method of open-ended problem solving.

Nordstrom and Korpelainen (2011) report that undergraduate engineering students were more highly engaged and motivated in open-ended problems requiring innovation as an incremental process. Their study focused on biotechnology students in Finland who worked in team settings to solve engineering problems and then presented the results with humorous and unconventional presentation methods. *Standards for Technological Literacy* (ITEA/ITEEA, 2000/2002/2007) includes discussion and direct benchmarks on creativity, e.g.; Standard 1H: Technology is closely linked to creativity, which has resulted in innovation, and Standard 9J: Engineering design is influenced by personal characteristics, such as creativity, resourcefulness, and the ability to think abstractly.

OPTIMISM

Optimism is commonly thought of as the world view of someone who sees the cup as half full. In other words, these cheerful individuals tend to see the world around them as a positive place. This optimistic view can provide benefits to individuals. For example, optimism is a contributing factor in a stronger sense of control by cancer patients over their cure (Henselmans et al, 2010). In the context of engineering, optimism is a "world view in which possibilities and opportunities can be found in every challenge and an understanding that every technology can be improved (The National Academy of Engineering, 2010, p. 45). Lu (2009) reported on a study at Virginia Tech that indicated that freshman engineering students had overwhelmingly positive and enthusiastic perceptions (91%) about nanotechnology as a future industry and a way to change society in a positive direction. Lu noted that when questions about potential ethics issues with nanotechnology were raised, student enthusiasm waivered. Other authors cautioned against the arrogance of optimism, wishful thinking, and hope in engineering design (Landau & Chisholm, 1995, Shull, 2011, Dearden, 2011). As a habit of mind in engineering, it is important therefore to distinguish between unquestioned acceptance for technological change and thoughtful understanding of all aspects of change.

An alternative way to view optimism is to define it as motivation to succeed or persist. By this definition, an engineering student tackles an engineering challenge with a dedicated focus on solving the problem. The student is persistent in looking for solutions on how to improve technologies, whether a system, artifact, or outcome. This would be a more nuanced and understandable criteria for assessing the student than participation or effort. An appropriate standard would be *Advancing Excellence in Technological Literacy* (ITEA/ITEEA, 2003) Assessment Standard A-4C – Facilitate critical thinking and decision making.

COLLABORATION

According to the National Academy of Engineering (2010), collaboration in engineering "leverages the perspectives, knowledge, and capabilities of team members to address design challenges" (p. 45). In the current era of globalization, it is not uncommon for industry work teams to span many countries. With a horizontal structure of management, members of work teams have equal say in the design, development, production, and marketing of new innovations. Technology education teachers at the secondary level commonly group students in teams to work on technology and engineering problem-based projects. This grouping strategy is in alignment with strategies promoted by educational associations to develop student competencies in interpersonal skills through participation in team activities (Partnership for 21st Century Skills, 2013). Nordstrom and Korpelainen (2011) report that collaborative groups in engineering showed increased mutual respect for each other, developed a culture of "us" within groups, increased their understanding of difficult topics, developed complex team work situations, had better abilities to resolve conflicts, and exhibited increased empathy for others. The National Academy of Engineering (2010) states that in Grades 9-12, students should "show evidence that they recognize the advantages of the combination of teamwork and individual efforts, … focus on the quality of work by the entire team, and … engage and assist weaker members of the team" (p. 141). Collaborative groupings have been a useful teaching strategy in technology education for many years. The program standards in *Advancing Excellence in Technological Literacy* (ITEA/ITEEA, 2003) include Standard P-4a: "Create and manage learning environments that are supportive of student interactions …" (p. 87).

COMMUNICATION

Communication is a process in which people try to inform, educate, persuade, control, manage, and entertain. In engineering education design teams, communication occurs within teams and with the instructor. Practice 8 – Obtaining, Evaluating, and Communicating Information from *Next Generation Science Standards: For States, By States* (NGSS Lead States, 2013b) covers the importance of students communicating technical and scientific results of their designs. Communication as a principle in engineering education focuses on two ideas: a way to understand the wants and needs of a person needing the engineering work, and a means to explain and defend choices made in the design process. This principal habit of mind describes student communication occurring at two distinct points in a project: in the very beginning of the problem-analysis stage with the customer (instructor) and at the end, when final designs and prototypes are presented. In *STL* Standard 8H (ITEA/ITEEA, 2000/2002/2007) these two ideas bookmark the benchmark "The design process includes defining a problem … and communicating processes and results" (p. 97). In each case and throughout an engineering project, the ability to think critically is imperative.

Critical thinking involves logical thinking and reasoning, including skills such as comparison, classification, sequencing, cause/effect, patterning, webbing, analogies, deductive and inductive reasoning, forecasting, planning, hypothesizing, and critiquing. Creative thinking involves creating something new or original. It involves the skills of flexibility, originality, fluency, elaboration, brainstorming, modification, imagery, associative thinking, attribute listing, metaphorical thinking, and forced relationships. The aim of creative thinking is to stimulate curiosity and promote divergence. Nordstrom and Korpelainen (2011) report that when collaborative engineering groups communicated project results to peers, this facilitated group discussions, internalization of ideas by members, and increased students' own understanding of concepts.

ATTENTION TO ETHICS

The final principal habit of mind in engineering education is ethical considerations in technology and designs. Any new product or design must be viewed through a prism of its impact on people, systems, and the environment. The impacts could be unexpected and undesirable, becoming apparent only after implementation of the new technology in society. This engineering habit of mind could be considered a check on over-optimism about one's design. Students could be taught to conduct risk analyses on their designs; for example, considering disposal of waste from the engineering process. The idea of evaluating risks while paying attention to ethics is well represented in national content standards. Standards 4 and 5 of *Standards for Technological Literacy* (ITEA/ITEEA, 2000/2002/2007) cover the cultural, social, economic, and political effects of technology and the effects of technology on the environment. *Next Generation Science Standard* HS-ETS1-3 asks American high school graduates to be able to "evaluate a solution to a complex problem based on prioritized criteria and tradeoffs that account for a range of constraints, including cost, safety, reliability, and aesthetics, as well as possible social, cultural, and environmental impacts" (NGSS Lead State, 2012a, p. 291). Standard 9 of *Standards for K-12 Engineering Education* (2010) states that "Concern for societal and environmental impacts of technology involves personal values as well as knowledge and skills" (p. 141).

SECONDARY-LEVEL LESSONS

As noted earlier, the use of engineering design challenges supports the development of engineering habits of mind as described by the National Academy of Engineering (2010). Most of the suggested challenges described below can be linked to developing the engineering habits of mind: systems thinking, creativity, optimism, collaboration, communication, and attention to ethics. For example, a design challenge for students in work teams to design and develop a composite material from a varied selection of materials to span a set distance and support weight could include the teaching of all of the habits. The students would work in their team (collaborate) to brainstorm (creativity) a design (systems thinking) to solve (optimism) the challenge, accounting for the production cycle waste (ethics) of their material choices and presenting their findings (communicate) to the class. The instructor could construct a performance-based rubric to assess these engineering habits of mind to provide feedback to the students.

Using this same construct, many other design challenges could be utilized in secondary settings, including analysis of cost and benefits of production processes, risk management, studying the effects of oil dispersants on fish populations, building complex series and parallel electrical circuits using grapefruits to light LEDs, designing aerodynamic drones with video capabilities to study local traffic patterns, nanotechnology designs, comparisons of green energy technologies, robotics control, and more. While individual habits are included in Engineering byDesign™, i.e.; *Technology and Society*, Unit 1, Lesson 2 Ethics in Engineering, technology courses would benefit from the inclusion of the engineering habits of mind as normal practice in all engineering design challenges. Engineering and technology teachers could include supplementary activities and criteria in project-based rubrics to assess secondary students on meeting expectations for demonstrating engineering habits of mind. This would make habits of mind a crosscutting theme in all work, similar to a focus on technical reading, design steps, and critical thinking.

POSTSECONDARY LEVEL

Preservice teacher education in engineering and technology education at a university level prepares future teachers to teach technology education in public schools. In some states, technology education is a required credit at the high school level. This credit requirement is met by school districts through Engineering byDesign™ coursework and other curriculum. In order to prepare these future teachers to teach engineering habits of mind, it follows that preservice teachers should be taught instructional and assessment strategies through engineering design challenges. Teacher educators could intentionally include engineering habits of mind as a crosscutting theme throughout the instructional methods coursework. Preservice educators could be required to articulate how to teach and assess habits of mind at the middle and high school levels in engineering and technology classrooms.

ASSESSMENT

Students focus on what is important in engineering and technology classes, particularly work linked to assessments. Performance-based rubrics are an appropriate means of assessing students in engineering challenges. A decision the technology teacher would have to make is how much weight to assign the assessment criteria habits of mind. There are three ways to assess the habits utilizing a rubric. The first would combine all of the habits as one criteria with a modest or low weighting within the challenge evaluation. By doing this though, the descriptors of the levels would tend to be rather generic (Table 2).

Table 2: Example of Habits of Mind as one unified criteria in an engineering challenge rubric.

Criteria	Exemplary	Acceptable	Emergent	Unacceptable
Engineering Habits of Mind	Demonstrates complete and enduring modeling of systems thinking, creativity, optimism, collaboration, communication, and attention to ethics in the engineering challenge.	Models appropriate systems thinking, creativity, optimism, collaboration, communication, and attention to ethics in the engineering challenge.	Models some approximation of systems thinking, creativity, optimism, collaboration, communication, and attention to ethics in the engineering challenge.	Does not model or exhibit systems thinking, creativity, optimism, collaboration, communication, or attention to ethics in the engineering challenge.

The habits of mind could be combined into three subgroups, modeled on the Learning and Innovation Skills—4Cs in *Framework for 21st Century Learning* (Partnership for 21st Century Skills, 2013). These would be Critical Thinking, Communication, Collaboration, and Creativity. Of these, the last three would be a stand-alone match to the habits. The first criteria, critical thinking, would include systems thinking, optimism, and attention to ethics. This rubric would give added weight to the habits of mind (Table 3). In the third model rubric, all six habits would be evaluated as separate criteria, leading to an expanded rubric or reduced weight for work done in the design, processes, and reflection phases of the engineering challenge.

CONCLUSION

Engineering habits of mind are the essential skills of thinking and acting that engineers perform at work. With a new focus on Science, Technology, Engineering and Mathematics (STEM) curriculum, infusion of engineering concepts in technology education, and national content standards, it makes sense that engineering and technology teachers would teach the engineering habits of mind as introduced in *Standards for K-12 Engineering Education*. Similar in context to *Framework for 21st Century Learning* and other national calls to action, engineering habits of mind are meant to help prepare secondary students for post-secondary success in engineering, whether in college or in their future careers.

Engineering design challenges can help teachers address all of the habits in individual projects if thoughtfully planned and assessed. Engineering habits of mind could be taught and assessed throughout all lesson plans and design challenges similarly to the way that academic literacies are embedded in all coursework. The benefit to the field of technology and engineering would be that program completers will have developed useful skills to help them succeed in this global STEM world we live in.

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Table 3: Example of Habits of Mind as four criteria in an engineering challenge rubric, modeled from the Learning and Innovation Skills 4-C from the *Framework for 21st Century Learning.*

Criteria	Exemplary	Acceptable	Emergent	Unacceptable
Critical Thinking	Demonstrates and reflects understanding of systems thinking. Optimistic and persistent in ability to solve the challenge. Thoroughly evaluates risks and potential outcomes of chosen solutions.	Demonstrates an understanding of systems thinking. Fairly optimistic and persistent in ability to solve the challenge. Thinks about risks and potential outcomes of chosen solutions.	Has some idea what systems thinking is. Low confidence, therefore needing prompting to work on the challenge. Little consideration of risks and potential outcomes of chosen solutions.	Does not know what systems thinking is. No confidence in abilities, therefore little or no contribution to group work. No consideration of risks and potential outcomes of chosen solutions.
Communication	Command of oral and written language in all work. Contributes to discussion within and across groups. Demonstrates sophisticated use of educational technologies in presentations.	Acceptable use of oral and written language in engineering challenge work. Joins in discussion within group. Demonstrates use of educational technologies in presentations.	Poor use of either oral or written language in work. Minor or belated responses in discussions. Little or poor use of educational technologies in presentations.	Poor oral and written communication in all work. No contribution to discussions. No or inappropriate use of educational technologies in presentations.
Collaboration	Successfully leverages the perspectives, knowledge, and capabilities of all team members in the challenge.	Cooperates in team setting, completing assigned tasks.	Occasionally shows disrespect for others' views, reluctantly finishes or delays completing assigned tasks.	Demonstrates complete lack of participation in group work and assigned tasks. Tries to dominate (or) avoids group work.
Creativity	Uses imagination and ingenuity, going outside normal rules and conventions when brainstorming ideas in new, clever, and surprising ways.	Develops some original ideas for the engineering challenge in the design phase, but some ideas are predictable.	Reproduces conventional ideas and solutions, does not imagine new ones. May articulate tentative ideas on stepping outside the rules and conventions, but little follow-through.	Completely stays within existing conventions, no attempt to develop original ideas.

Engineering Habits of Mind in Engineering Challenges Rubric

Criteria	Target 4 pts	Acceptable 3 pts	Emergent 2 pts	Unacceptable 0-1 pt
Systems Thinking	Student can fully articulate all aspects of systems thinking: design, development, processes, consequences of development, and the interrelatedness of technology.	Student understands most aspects of systems thinking and can explain how technologies interrelate.	Student can explain some aspects of systems thinking, leaving out some of the principles.	Student cannot explain systems thinking, relying on a view of technology as simply a product or artifact.
Creativity	Designs were extremely clever and original; a unique approach that truly enhanced the project.	Designs showed some cleverness; thoughtfully and uniquely presented.	Student added few original touches to enhance the project but mostly followed conventions.	Little creative energy used during this project; was bland, predictable, and lacked "zip."
Optimism	Student tackles project with dedicated focus and enthusiasm. Exhibits persistence to improve design or project.	Student shows dedication to project. Thinks about how to improve design or project.	Student works on project as required but shows modest effort to complete project.	Student has no buy-in or enthusiasm for project and shows no interest in making improvements.
Collaboration	Cooperation and collaboration are routinized. Work is well coordinated, with all members equally sharing responsibilities. Class members are actively engaged in supporting each other, including weaker members.	Group agrees on assigned roles and shares workload.	Some teamwork, but one person dominates decision-making. Member responsibilities are uneven. Weak members are marginalized.	No teamwork or shared responsibilities. Each team member works in isolation from other members, resulting in duplicated work or incomplete projects. Members are mostly passive.
Communication	Students fully address the problem analysis in discussions with instructor and clearly communicate their project in their final presentation.	Students discuss the problem analysis with instructor and communicate their project in their final presentation.	Students are not fully able to articulate their problem analysis or communicate their project in presentation.	Students unable to explain to instructor their problem analysis and do not communicate their ideas in their final presentation.
Attention to Ethics	Students conduct detailed risk analysis and can articulate thorough impacts of their design, whether environmental or undesirable.	Students conduct risk analysis and can articulate impacts of their design, whether environmental or undesirable.	Students think about risk analysis but only provide generalities on the impacts of their design.	Students don't consider risk analysis and can therefore provide little or no information on the impacts of their design.