Engage with Engineering: Preparing a Science Department to Integrate Engineering Practices into its Courses

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The Marshmallow Challenge

1. Your Materials: 20 sticks of spaghetti, one meter of masking tape, one meter of string, and one marshmallow.

2. Build the Tallest Freestanding Structure: The winning team is the one that has the tallest structure measured from the tabletop surface to the top of the marshmallow. That means the structure cannot be suspended from a higher structure, like a chair, ceiling or chandelier.

3. The Entire Marshmallow Must be on Top: The entire marshmallow needs to be on the top of the structure. Cutting or eating part of the marshmallow disqualifies the team.

4. Use as Much or as Little of the Kit: The team can use as many or as few of the 20 spaghetti sticks, as much or as little of the string or tape. If materials are delivered in a paper bag, the team cannot use the paper bag as part of their structure.

5. Break up the Spaghetti, String or Tape: Teams are free to break the spaghetti, cut up the tape and string to create new structures.

6. The Challenge Lasts 18 minutes: Teams cannot hold on to the structure when the time runs out. Those touching or supporting the structure at the end of the exercise will be disqualified.

7. Remind the Teams that Holders will be Disqualified: Several teams will have the powerful desire to hold on to their structure at the end. Usually because the marshmallow, which they just placed onto their structure moments before, causing the structure to buckle. The winning structure needs to be stable.

For more information about The Marshmallow Challenge: http://marshmallowchallenge.com/TED_Talk.html
Context Setting Protocol
(Adapted from the Goal Setting Protocol, School Reform Initiative)

Process
1. Overview of where we have been and where we are heading. (Leader)

2. Individually brainstorm answers to the following 4 questions:
   1. What is Science?
   2. What is Engineering?
   3. Why do we teach science? (or more accurately, why do/should high school students study science?)
   4. Why do we teach engineering? (or more accurately, why do/should high school students study engineering?)
   You can have more than one answer/reason for each question. (10 Minutes)

3. Discuss the answers in triads, 3 minutes per person, talking through the answers people generated during the brainstorm. (10 Minutes)

4. Individuals put one choice/idea/answer/reason for each question on post-it notes. People can write something from their own brainstorm, or put up something that was discussed in their triad. Place the post-its on the chart paper. As you place the post-its, try to group similar ones together. (5 minutes)

5. Break into 4 groups. Each group categorizes, summarizes, and simplifies one chart paper. (10 minutes)

6. Groups share out the results. (10 minutes)

7. Wrap-up (5 minutes)

Note: I adapt many protocols from the School Reform Initiative to use in PD in my district. Find out more about SRI here: http://www.schoolreforminitiative.org/

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Brainstorm

1. What is Science?

2. What is Engineering?

3. Why do we teach science? (or more accurately, why do/should high school students study science?)

4. Why do we teach engineering? (or more accurately, why do/should high school students study engineering?)
Diving Into the Science and Engineering Practices

Three different mini-activities:

- Compare and Contrast the Practices.
  - Read the Two Page version of the Science and Engineering Practices.
  - Create a Venn Diagram for each practice. (small groups. Each group gets a practice to analyze)
- Transform a lab.
  - Preparation
    - Presenter chooses a common lab (good physics example = electromagnets).
    - Look for opportunities to expand or transform the lab and integrate the science and engineering practices more explicitly.
  - PD: Start by sharing the example and then have participants do their own.
- Identify opportunities in your own curriculum.
  - Read the two-page version of the science and engineering practices.
  - Identify places in your curriculum where you already do engineering and/or where there are “easy” opportunities.

NGSS Infusion

Two different mini-activities:

- Examination of Engineering Infused Science Performance Expectations
  - Break teachers into groups by discipline and/or grade level.
  - Ask teachers to examine the performance expectations in their discipline that have engineering infusion.
  - Use MicroLab Protocol to Debrief.
    (http://schoolreforminitiative.org/doc/microlabs.pdf)
    - 1. Is there anything in our current curriculum that matches this PE and/or could EASILY be changed to relate to this PE?
    - 2. Unwrap this PE. What content knowledge and skills are necessary pre-requisites?
    - 3. What do you think? Can we do this?
- Criteria for Success
  - Divide teachers into groups by discipline and/or grade level.
  - Assign an engineering infused PE to each small group.
  - Each group should work together to develop the criteria for success for that PE. What would student work look like? What could it include?
  - Could translate into developing possible projects and lesson plans.
  - Use tuning protocol to compare the lessons/projects with the performance expectations. (http://schoolreforminitiative.org/doc/tuning.pdf)

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K-12 Framework Jigsaw

Use this jigsaw to read and digest the “Disciplinary Core Idea – Engineering, Technology, and Application of Science” section of the Framework.

Preparation:
- Photocopy the DCI ETS section of the Framework. (starts on page 201.)
- Divide your group into five groups. Each group will have a different reading.
- Everyone should read the first 4 pages (introduction). Then, each group reads about a different DCI (1A, 1B, 1C, 2A, 2B)
- To be most efficient, have teachers complete the reading before the meeting. If not possible, reading time can be built into your agenda.
- Choose videos. Sources include:
  - http://focusforwardfilms.com/
  - Argonne National Laboratory on YouTube (http://www.youtube.com/watch?v=jiC4j3C_0D4&list=PLiuLoHBTSJsl9qNsxE4iLG3b-d1q_kqj&index=1)
  - IDEO Grocery Cart (available on YouTube)

Possible Formats:

<table>
<thead>
<tr>
<th>Longest</th>
<th>Medium</th>
<th>Shorter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Read</td>
<td>1. Expert groups</td>
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<tr>
<td>2. Expert groups</td>
<td>2. Jigsaw groups</td>
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<td>3. Jigsaw groups</td>
<td>3. Apply to the video</td>
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<td>4. Apply to the video</td>
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</tbody>
</table>

Directions for the teachers:
1. Read your assigned section of the K-12 Framework. You are all reading from DCI ETS (Disciplinary Core Idea – Engineering, Technology, and Application of Science)
   - 5 different readings (1A, 1B, 1C, 2A, 2B)
   - Read your assigned section
   - Be prepared to summarize.
2. (optional) Gather with a group of teachers who read the same reading. Decide on the 3 most important points to share with your colleagues.
3. Meet with a jigsaw group. Each person will share the 3 most important points from their reading with the group.
4. We will watch a number of short engineering videos. Be prepared to discuss, in your small group, how your reading applied to the video.

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Modified “Change in Practice” Protocol

Preparation before today: Choose a lesson/unit that you think applies engineering design practices or could benefit from this. Be prepared to describe the unit to your small group.

Essential Question: Where do engineering practices currently exist? Where can they exist?

Part #1: Individual Presentations
Timing is important; each round may last no more than 15 minutes.

1. You are in a group of 4 to 5 participants. Choose a timekeeper (who also participates) who has a watch. This job can rotate.
2. When the group is ready, a volunteer member shares his curriculum unit that applies the Engineering Design Process with the group. (1 person in your group is prepared to do this.) The presenter should spend no more than 7 minutes presenting to the group.
3. The other participants each have 1 minute to respond to the presentation — saying what it makes them think about, what questions it raises for them, what questions they have, etc.
4. The first participant then has 5 minutes to respond to the comments and questions of the other participants.
5. The same pattern is followed until all four members of the group have had a chance to be the presenter and to have “the last word.” Subsequent presenters may also be sharing an existing example of embedded EDP or may be sharing a lesson/unit where they would like to add EDP.
6. If time allows, optional open dialogue about the presentations and the ideas and questions raised.

Part #2: Small Group Processing
As a group, answer the following three questions and chart your responses on a piece of chart paper:
1. What new insights occurred for all of us?
2. Where can the engineering design process be used in your unit?
3. Who can you work with to plan and try this out?
Hang your responses on the wall in second floor hall.

Part #3: Gallery Walk
Walk from room to room and read the responses of the other groups. Spend about 20 minutes walking and reading. Think about the following:
- What new ideas can I use in my own work with students
- What will students know and be able to do by the end of their K-12 STE Education?

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Appendices:

1. 2-page version of the science and engineering practices. (from the NRC Framework)
2. Venn Diagram
3. Examples of Engineering Infused Science Performance Expectations
4. SRI MicroLab Protocol
5. SRI Tuning Protocol

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BOX 3.3

DISTINGUISHING PRACTICES IN SCIENCE FROM THOSE IN ENGINEERING

1. Asking Questions and Defining Problems

Science begins with a question about a phenomenon, such as "Why is the sky blue?" or "What causes cancer?", and seeks to develop theories that can provide explanatory answers to such questions. A basic practice of the scientist is formulating empirically answerable questions about phenomena, establishing what is already known, and determining what questions have yet to be satisfactorily answered.

Engineering begins with a problem, need, or desire that suggests an engineering problem that needs to be solved. A societal problem such as reducing the nation's dependence on fossil fuels may engender a variety of engineering problems, such as designing more efficient transportation systems, or alternative power generation devices such as improved solar cells. Engineers ask questions to define the engineering problem, determine criteria for a successful solution, and identify constraints.

2. Developing and Using Models

Science often involves the construction and use of a wide variety of models and simulations to help develop explanations about natural phenomena. Models make it possible to go beyond observables and imagine a world not yet seen. Models enable predictions of the form "If . . . then . . ." therefore to be made in order to test hypothetical explanations.

Engineering makes use of models and simulations to analyze existing systems so as to see where flaws might occur or to test possible solutions to a new problem. Engineers also call on models of various sorts to test proposed systems and to recognize the strengths and limitations of their designs.

3. Planning and Carrying Out Investigations

Scientific investigation may be conducted in the field or the laboratory. A major practice of the scientist is planning and carrying out a systematic investigation, which requires the identification of what is to be recorded and, if applicable, what are to be treated as the dependent and independent variables (control of variables). Observations and data collected from such work are used to test existing theories and explanations or to revise and develop new ones.

Engineers use investigation both to gain data essential for specifying design criteria or parameters and to test their designs. Like scientists, engineers must identify relevant variables, decide how they will be measured, and collect data for analysis. Their investigations help them to identify new, effective, efficient, and durable device designs, and they may be under a range of conditions.

4. Analyzing and Interpreting Data

Scientific investigations produce data that must be analyzed in order to derive meaning. Because data are usually not entirely new, scientists use a range of tools— including tabulation, graphical representation, visualization, and statistical analysis—to identify significant features and patterns in the data. Sources of error are identified and the degree of certainty calculated. Modern technology makes the collection of large data sets much easier, thus providing many secondary sources for analysis.

Engineers analyze data collected in the tests of their designs and investigations; this allows them to compare different solutions and determine which one meets specific design criteria—that is, which design best solves the problem within the given constraints. Like scientists, engineers require a range of tools to identify the major patterns and interpret the results.

5. Using Mathematics and Computational Thinking

In science, mathematics and computation are fundamental tools for representing physical variables and their relationships. They are used for a range of tasks, such as constructing simulations, statistically analyzing data, and recognizing, expressing, and applying quantitative relationships. Mathematical and computational approaches enable predictions of the behavior of physical systems, along with the testing of such predictions. Moreover, statistical techniques are invaluable for assessing the significance of patterns or correlations.

In engineering, mathematical and computational representations of established relationships and principles are an integral part of design. For example, structural engineers create mathematically based analyses of designs to determine whether they can stand up to the expected stresses of use and if they can be completed within acceptable budgets. Moreover, simulations of designs provide an effective test bed for the development of designs and their improvement.
6. Constructing Explanations and Designing Solutions

The goal of science is the construction of theories that can provide explanatory accounts of features of the world. A theory becomes accepted when it has been shown to be superior to other explanations in the breadth of phenomena it accounts for and in its explanatory coherence and parsimony. Scientific explanations are explicit applications of theory to a specific situation or phenomenon, perhaps with the intermediary of a theory-based model for the system under study. The goal for students is to construct logically coherent explanations of phenomena that incorporate their current understanding of science, or a model that represents it, and are consistent with the available evidence.

Engineering design, a systematic process for solving engineering problems, is based on scientific knowledge and models of the material world. Each proposed solution results from a process of balancing competing criteria of desired functions, technological feasibility, cost, safety, aesthetics, and compliance with legal requirements. There is usually no single best solution but rather a range of solutions. Which one is the optimal choice depends on the criteria used for making evaluations.

7. Engaging in Argument from Evidence

In science, reasoning and argument are essential for identifying the strengths and weaknesses of a line of reasoning and for finding the best explanation for a natural phenomenon. Scientists must defend their explanations, formulate evidence based on a solid foundation of data, examine their own understanding in light of the evidence and comments offered by others, and collaborate with peers in searching for the best explanation for the phenomenon being investigated.

In engineering, reasoning and argument are essential for finding the best possible solution to a problem. Engineers collaborate with their peers throughout the design process, with a critical stage being the selection of the most promising solution among a field of competing ideas. Engineers use systematic methods to compare alternatives, formulate evidence based on test data, make arguments from evidence to defend their conclusions, evaluate critically the ideas of others, and revise their designs in order to achieve the best solution to the problem at hand.

8. Obtaining, Evaluating, and Communicating Information

Science cannot advance if scientists are unable to communicate their findings clearly and persuasively or to learn about the findings of others. A major practice of science is thus the communication of ideas and the results of inquiry—oral or in writing, with the use of tables, diagrams, graphs, and equations, and by engaging in extended discussions with scientific peers. Science requires the ability to derive meaning from scientific texts (such as papers, the Internet, symposia, and lectures), to evaluate the scientific validity of the information thus acquired, and to integrate that information.

Engineers cannot produce new or improved technologies if the advantages of their designs are not communicated clearly and persuasively. Engineers need to be able to express their ideas, orally and in writing, with the use of tables, graphs, drawings, or models and by engaging in extended discussions with peers. Moreover, as with scientists, they need to be able to derive meaning from colleagues’ texts, evaluate the information, and apply it productively in engineering and science alike, new technologies are now routinely available that extend the possibilities for collaboration and communication.
NGSS Infusion

Sample “Engineering Infused Science Performance Expectations”

K-PS2-2. Analyze data to determine if a design solution works as intended to change the speed or direction of an object with a push or a pull.*

K-ESS3-3. Communicate solutions that will reduce the impact of humans on the land, water, air, and/or other living things in the local environment.*

2-LS2-2. Develop a simple model that mimics the function of an animal in dispersing seeds or pollinating plants.*

2-ESS2-1. Compare multiple solutions designed to slow or prevent wind or water from changing the shape of the land.*

4-PS3-4. Apply scientific ideas to design, test, and refine a device that converts energy from one form to another.*

4-PS4-3. Generate and compare multiple solutions that use patterns to transfer information.*

MS-PS1-6. Undertake a design project to construct, test, and modify a device that either releases or absorbs thermal energy by chemical processes.*

MS-LS2-5. Evaluate competing design solutions for maintaining biodiversity and ecosystem services.*

HS-PS1-6. Refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium.*

HS-PS2-3. Apply scientific and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.*

HS-LS2-7. Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity.*

HS-LS4-6. Create or revise a simulation to test a solution to mitigate adverse impacts of human activity on biodiversity.*

HS-ESS3-2. Evaluate competing design solutions for developing, managing, and utilizing energy and mineral resources based on cost-benefit ratios.*

Microlabs

Developed by Julian Weissglass for the National Coalition for Equity in Education based at the University of California, Santa Barbara; adapted in the field by educators.

Purpose
Microlabs addresses a specific sequence of questions in a structured format with small groups, using active listening skills.

Time
About 8 minutes per question — this works best with a series of no more than 3 questions.

Group Format
Form triads — either with the people you’re sitting near, or find others in the group you don’t know well. Number off within your triad: 1, 2, 3.

Facilitation
The facilitator should spend time developing a sequence of questions that are appropriate for the purpose or focus of the conversation. The questions should be ones that are important to the group, and that spiral in depth from first to last.

The facilitator says, “I’ll direct what we will talk about. Each person will have 1 minute (or, sometimes, 2 minutes, depending on the group and the question) to talk about a question when it’s their turn. While the person is speaking, the other 2 in the group simply listen. When the time is up, the next person speaks, and so on. I’ll tell you when to switch.” Emphasize that talk has to stop when you call time, and conversely, that if the person is done speaking before time is up, the triad should sit in silence, using the time to reflect.

It’s nice to have a chime to ring to indicate that time is up.

Process
After instructing the group, read the first question aloud (twice). Give everyone time to think or write in preparation. Then, tell people when to begin, and then tell them when each 1-2 minute segment is up. On the first question, begin with person #1, then #2, then #3. Then read the next question aloud. On the second question, begin with #2, then #3, then #1. On the third question, begin with #3, then #1, then #2.

Debrief
• What did you hear that was significant? What key ideas or insights were shared?
• How did this go for you? What worked well, and what was difficult? Why?
• How might your conversations have been different had we not used this protocol?
• What are the advantages/disadvantages of using this activity? When would you use this protocol?
• What would you want to keep in mind as someone facilitating this activity?

Protocols are most powerful and effective when used within an ongoing professional learning community and facilitated by a skilled facilitator. To learn more about professional learning communities and seminars for facilitation, please visit the School Reform Initiative website at www.schoolreforminitiative.org.
Tuning Protocol

Developed by Joseph McDonald, Coalition of Essential Schools; Revised by David Allen.

Description
The Tuning Protocol was originally developed as a means for the 5 high schools in the Coalition of Essential School's Exhibitions Project to receive feedback and fine-tune their developing student assessment systems, including exhibitions, portfolios, and design projects. Recognizing the complexities involved in developing new forms of assessment, the project staff developed a facilitated process to support educators in sharing their students’ work (sometimes students brought their own work) and, with colleagues, reflect upon the lessons that are embedded there. This collaborative reflection helps educators design and refine their assessment systems, and supports higher quality student performance. Since its trial run in 1992, the Tuning Protocol has been widely used and adapted for looking at both student and adult work in and among schools across the country.

Note: If adult work (such as an adult developed document like a lesson plan, rubric, newsletter, etc.) is the focus and there are no student work samples, you may want to consider the Tuning Protocol: Examining Adult Work.

Process
1. Introduction (5 minutes)
   Facilitator briefly introduces protocol goals, guidelines, and schedule

2. Presentation (10-15 minutes)
   The presenter has the opportunity to share both the context for her work and any supporting documents as warranted, while participants are silent.
   • Information about the students and/or the class — what the students tend to be like, where they are in school, where they are in the year.
   • Assignment or prompt that generated the student work
   • Student learning goals or standards that inform the work
   • Samples of student work — photocopies of work, video clips, etc. — with student names removed
   • Evaluation format — scoring rubric and or assessment criteria, etc.
   • Focusing question for feedback (ex: To what extent does the student work reflect the learning standards? Or, How might the rubric be in closer alignment to the skills and knowledge present in the student work?) is shared and posted for all to see.

3. Clarifying Questions (3-5 minutes)
   • Participants have an opportunity to ask clarifying questions in order to get information that may have been omitted during the presentation and would help them to better understand the work.
   • Clarifying questions are matters of fact.
   • The facilitator is responsible for making sure that clarifying questions are really clarifying and not warm/cool feedback or suggestions.

Protocols are most powerful and effective when used within an ongoing professional learning community and facilitated by a skilled facilitator. To learn more about professional learning communities and seminars for facilitation, please visit the School Reform Initiative website at www.schoolreforminitiative.org.
4. Examining the Work (10-15 minutes)
Participants look closely at the work, making notes on where it seems to be “in tune” or aligned with the stated goals and, guided by the presenter’s focusing question and goals, where there might be a potential disconnect.
Note: It’s possible that participants could have an additional clarifying question or 2 during this time. If so, the facilitator might offer an additional moment for these to be asked by participants and answered by the presenter.

5. Pause to Silently Reflect on Warm and Cool Feedback (2-3 minutes)
- Participants individually review their notes and decide what they would like to contribute to the feedback session.
- Presenter is silent.
- Participants do this work silently.

6. Warm and Cool Feedback (10-15 minutes)
- Participants share feedback with each other while the presenter is silent and takes notes. The feedback generally begins with a few minutes of warm feedback, moves on to a few minutes of cool feedback (sometimes phrased in the form of reflective questions), and then moves back and forth between warm and cool feedback.
- Warm feedback may include comments about how the work presented seems to align with the desired goals; cool feedback may include possible disconnects, gaps, or problems. Often participants offer ideas or suggestions for strengthening the work presented, so long as the suggestions are guided by the presenter’s goals and question.
- It might be helpful for the facilitator to offer prompts for the feedback, such as:
  - **Warm feedback**
    - “It seems important…”
    - “I appreciate…”
    - “I want to make sure to keep…”
  - **Cool feedback**
    - “I wonder if…”
    - “One way to more closely align the goal/purpose is…”
- The facilitator may need to remind participants of the presenter’s focusing question.
- Presenter is silent, listening in on the conversation and taking notes.

7. Reflection (3-5 minutes)
- Presenter rejoins the group and shares her/his new thinking about what she/he learned from the participants’ feedback.
- This is not a time for the presenter to defend her/himself, but is instead a time for the presenter to reflect aloud on anything that seemed particularly interesting.
- Facilitator may need to remind participants that once the work has been returned to the presenter, there will be no more feedback offered.

8. Debrief (3-5 minutes)
Facilitator leads discussion about this tuning experience.

*Note: See Tuning Protocol Guidelines for information on effective participation in a Tuning.*
Dimension 3
DISCIPLINARY CORE IDEAS—ENGINEERING, TECHNOLOGY, AND APPLICATIONS OF SCIENCE

In Chapter 3, we assert that "any (science) education that focuses predominately on the detailed products of scientific labor—the facts of science—without developing an understanding of how those facts were established or that ignores the many important applications of science in the world misrepresents science and misrecognizes the importance of engineering." This statement has two implications for science education standards in general and for this report's framework in particular. The first is that students should learn how scientific knowledge is acquired and how scientific explanations are developed. The second is that students should learn how science is utilized, in particular through the engineering design process, and they should come to appreciate the distinctions and relationships between engineering, technology, and applications of science (ETS). These three terms are defined in Box 8-1.

Chapter 3 describes how an understanding of engineering practices can develop as they are used in the classroom to help students acquire and apply science knowledge. There is also a domain of knowledge related to these practices, and it constitutes the framework's first ETS core idea—ETS1: Engineering Design. Although there is not yet broad agreement on the full set of core ideas in engineering [1], an emerging consensus is that design is a central practice of engineering; indeed, design is the focus of the vast majority of K-12 engineering curricula currently in use. The committee is aware that engineers not only design new technologies, but they also sometimes fabricate, operate, inspect, and maintain them. However, from a teaching and learning point of view, it is the iterative cycle of design that offers the greatest potential for applying science knowledge in the classroom and engaging in engineering practices. The components of this core idea include understanding how engineering problems are defined and delimited, how models can be used to develop and refine possible solutions to a design problem, and what methods can be employed to optimize a design.

The second ETS core idea calls for students to explore, as its name implies, the "Links Among Engineering, Technology, Science, and Society" (ETS2). The applications of science knowledge and practices to engineering, as well as to such areas as medicine and agriculture, have contributed to the technologies and the systems that support them that serve people today. Insights gained from scientific discovery have altered the ways in which buildings, bridges, and cities are constructed; changed the operations of factories; led to new methods of generating and distributing energy; and created new modes of travel and communication. Scientific insights have informed methods of food production, waste disposal, and the diagnosis and treatment of disease. In other words, science-based, or science-improved, designs of technologies and systems affect the ways in which people interact with each other and with the environment, and thus these designs deeply influence society.

In turn, society influences science and engineering. Societal decisions, which may be shaped by a variety of economic, political, and cultural factors, establish goals and priorities for technologies' improvement or replacement. Such decisions also set limits—in controlling the extraction of raw materials, for example, or in setting allowable emissions of pollution from mining, farming, and industry. Goals, priorities, and limits are needed for regulating new technologies, which can
have deep impacts on society and the environment. The impacts may not have
been anticipated when the technologies were introduced (e.g., refrigerant gases
that depleted stratospheric ozone) or may build up over time to levels that require
mitigation (toxic pesticides, lead in gasoline). Thus the balancing of technologies’
costs, benefits, and risks is a critical element of ETS2. Box K-2 summarizes the
framework’s two ETS core ideas and their components.

The fields of science and engineering are mutually supportive. New tech-
nologies expand the reach of science, allowing the study of realms previously
inaccessible to investigation; scientists depend on the work of engineers to produce
the instruments and computational tools they need to conduct research. Engineers
in turn depend on the work of scientists to understand how different technolo-
gies work so they can be improved; scientific discoveries are exploited to create
new technologies in the first place. Scientists and engineers often work together in
teams, especially in new fields, such as nanotechnology or synthetic biology that
blur the lines between science and engineering. Students should come to under-
stand these interactions and at increasing levels of sophistication as they mature.
Their appreciation of the interface of science, engineering, and society should give
them deeper insights into local, national, and global issues.

The 2010 National Academy of Engineering report Standards for K-12
Engineering Education [1] concluded that it is not appropriate at present to
develop standards for K-12 engineering education. But the report also made it clear
that engineering concepts and skills are already embedded in existing standards for
science and technology education, at both the state and national levels—and the
report recommended that this practice continue. In addition, it affirmed the value
of teaching engineering ideas, particularly engineering design, to young students.
In line with those conclusions and recommendations, the goal of this section of
the framework—and of this chapter—is not to replace current K-12 engineering
and technology courses. The chapter’s goal is rather to strengthen the science edu-
cation provided to K-12 students by making the connections between engineering,
technology, and applications of science explicit, both for standards developers and
curriculum developers. In that way, we hope to ensure that all students, whatever
their path through K-12 education, gain an appreciation of these connections.

Core Idea ETS1 Engineering Design

How do engineers solve problems?

The design process—engineers’ basic approach to problem solving—includes many
different practices. They include problem definition, model development and use,
investigation, analysis and interpretation of data, application of mathematics and
computational thinking, and determination of solutions. These engineering prac-
tices incorporate specialized knowledge about criteria and constraints, modeling
and analysis, and optimization and trade-offs.

ETS1.A: Defining and Delimiting an Engineering Problem

What is a design task?

What are the criteria and constraints of a successful solution?

The engineering design process begins with the identification of a problem to solve
and the specification of clear goals, or criteria, that the final product or system
must meet. Criteria, which typically reflect the needs of the expected end-user of
a technology or process, address such things as how the product or system will
function (what job it will perform and how), its durability, and its cost. Criteria
should be quantifiable whenever possible and stated so that one can tell if a given
design meets them.
Engineers must contend with a variety of limitations, or constraints, when they engage in design. Constraints, which frame the salient conditions under which the problem must be solved, may be physical, economic, legal, political, social, ethical, aesthetic, or related to time and place. In terms of quantitative measurements, constraints may include limits on cost, size, weight, or performance, for example. And although constraints place restrictions on a design, not all of them are permanent or absolute.

**Grade Band End Points for ETS1.A**

*By the end of grade 2.* A situation that people want to change or create can be approached as a problem to be solved through engineering. Such problems may have many acceptable solutions. Asking questions, making observations, and gathering information are helpful in thinking about problems. Before beginning to design a solution, it is important to clearly understand the problem.

*By the end of grade 5.* Possible solutions to a problem are limited by available materials and resources (constraints). The success of a designed solution is determined by considering the desired features of a solution (criteria). Different proposals for solutions can be compared on the basis of how well each one meets the specific criteria for success or how well each takes the constraints into account.

*By the end of grade 8.* The more precisely a design task's criteria and constraints can be defined, the more likely it is that the designed solution will be successful. Specification of constraints includes consideration of scientific principles and other relevant knowledge that are likely to limit possible solutions (e.g., familiarity with the local climate may rule out certain plants for the school garden).

*By the end of grade 12.* Design criteria and constraints, which typically reflect the needs of the end-user of a technology or process, address such things as the product's or system's function (what it will perform and how), its durability, and limits on its size and cost. Criteria and constraints also include satisfying any requirements set by society, such as taking issues of risk mitigation into account, and they should be quantified to the extent possible and stated in such a way that one can tell if a given design meets them.

Humanity faces major global challenges today, such as the need for supplies of clean water and food or for energy sources that minimize pollution, which can be addressed through engineering. These global challenges also may have manifestations in local communities. But whatever the scale, the first thing that engineers do is define the problem and specify the criteria and constraints for potential solutions.

**ETS1.B: DEVELOPING POSSIBLE SOLUTIONS**

What is the process for developing potential design solutions?

The creative process of developing a new design to solve a problem is a central element of engineering. This process may begin with a relatively open-ended phase during which new ideas are generated both by individuals and by group processes such as brainstorming. Before long, the process must move to the specification of solutions that meet the criteria and constraints at hand. Initial ideas may be communicated through informal sketches or diagrams, although they typically become more formalized through models. The ability to build and use physical, graphical, and mathematical models is an essential part of translating a design idea into a finished product, such as a machine, building, or any other working system. Because each area of engineering focuses on particular types of systems (e.g., mechanical, electrical, bioengineering), engineers become expert in the elements that such systems need. But whatever their fields, all engineers use models to help develop and communicate solutions to design problems.

Models allow the designer to better understand the features of a design problem, visualize elements of a possible solution, predict a design's performance, and guide the development of feasible solutions (or, if possible, the optimal solution). A physical model can be manipulated and tested for parameters of interest, such as strength, flexibility, heat conduction, fit with other components, and durability. Scale models and prototypes are particular types of physical models. Graphical models, such as sketches and drawings, permit engineers to easily share and discuss design ideas and so rapidly review their thinking based on input from others.

Mathematical models allow engineers to estimate the effects of a change in one feature of the design (e.g., material composition, ambient temperature) or other features, or on performance as a whole, before the designed product...
Models allow the designer to better understand the features of a design problem, visualize elements of a possible solution, predict a design's performance, and guide the development of feasible solutions.

is actually built. Mathematical models are often embedded in computer-based simulations. Computer-aided design (CAD) and computer-aided manufacturing (CAM) are modeling tools commonly used in engineering.

Data from models and experiments can be analyzed to make decisions about modifying a design. The analysis may reveal performance information, such as which criteria a design meets, or predict how well the overall designed system or system component will perform under certain conditions. If analysis reveals that the predicted performance does not align with desired criteria, the design can be adjusted.

**Grade Band Endpoints for ETS1.B**

**By the end of grade 2.** Designs can be conveyed through sketches, drawings, or physical models. These representations are useful in communicating ideas for a problem's solutions to other people. To design something complicated, one may need to break the problem into parts and attend to each part separately but then bring the parts together to see the overall plan.

**By the end of grade 5.** Research on a problem should be carried out—for example, through Internet searches, market research, or field observations—before beginning to design a solution. An often productive way to generate ideas is for people to work together to brainstorm, test, and refine possible solutions. Testing a solution involves investigating how well it performs under a range of likely conditions. Tests are often designed to identify failure points or difficulties, which suggest the elements of the design that need to be improved. At whatever stage, communicating with peers about proposed solutions is an important part of the design process, and shared ideas can lead to improved designs.

There are many types of models, ranging from simple physical models to computer models. They can be used to investigate how a design might work, communicate the design to others, and compare different designs.

**By the end of grade 6.** A solution needs to be tested and then modified on the basis of the test results, in order to improve it. There are systematic processes for evaluating solutions with respect to how well they meet the criteria and constraints of a problem. Sometimes parts of different solutions can be combined to create a solution that is better than any of its predecessors. In any case, it is important to be able to communicate and explain solutions to others.

Models of all kinds are important for testing solutions, and computers are a valuable tool for simulating systems. Simulations are useful for predicting what would happen if various parameters of the model were changed, as well as for making improvements to the model based on peer and teacher (e.g., feedback).

**By the end of grade 12.** Complicated problems may need to be broken down into simpler components in order to develop and test solutions. When evaluating solutions, it is important to take into account a range of constraints, including cost, safety, reliability, and aesthetics, and to consider social, cultural, and environmental impacts. Testing should lead to improvements in the design through an iterative procedure.

Both physical models and computers can be used in various ways to aid in the engineering design process. Physical models, or prototypes, are helpful in testing product ideas or the properties of different materials. Computers are useful for a variety of purposes, such as in representing a design in 3-D through CAD software, in troubleshooting to identify and describe a design problem, in running simulations to test different ways of solving a problem, or to see which one is most efficient or economical, and in making a persuasive presentation to a client about how a given design will meet his or her needs.

**ETS1.C: OPTIMIZING THE DESIGN SOLUTION**

How can the various proposed design solutions be compared and improved?
Multiple solutions to an engineering design problem are always possible because there is more than one way to meet the criteria and satisfy the constraints. But the aim of engineering is not simply to design a solution to a problem but to design the best solution. Determining what constitutes “best,” however, requires value judgments, given that one person’s view of the optimal solution may differ from another’s.

Optimization often requires making trade-offs among competing criteria. For example, as one criterion (such as lighter weight) is enhanced, another (such as unit cost) might be sacrificed (i.e., cost may be increased due to the higher cost of lightweight materials). In effect, one criterion is revised or traded off for another that is deemed more important. When multiple possible design options are under consideration, each optimized for different criteria, engineers may use a trade-off matrix to compare the overall advantages and disadvantages of the different proposed solutions.

The decision as to which criteria are critical and which ones can be traded off is a judgment based on the situation and the perceived needs of the end-user of the product or system. Because many factors—including environmental or health impacts, available technologies, and the expectations of users—change over time and vary from place to place, a design solution that is considered optimal at one time and place may appear far from optimal at other times and places. Thus different designs, each of them optimized for different conditions, are often needed.

**Grade Band Endpoints for ETS1.C**

- **By the end of grade 3:** Because there is always more than one possible solution to a problem, it is useful to compare designs, test them, and discuss their strengths and weaknesses.

- **By the end of grade 5:** Different solutions need to be tested in order to determine which of them best solves the problem, given the criteria and the constraints.

- **By the end of grade 8:** There are systematic processes for evaluating solutions with respect to how well they meet the criteria and constraints of a problem. Computing different designs could involve running them through the same kinds of tests and systematically recording the results to determine which design performs best. Although one design may not perform the best across all tests, identifying the characteristics of the design that performed the best in each test can provide useful information for the redesign process—that is, some of those characteristics may be incorporated into the new design. This iterative process of testing the most promising solutions and modifying what is proposed on the basis of the test results leads to greater refinement and ultimately to an optimal solution. Once such a suitable solution is determined, it is important to describe that solution, explain how it was developed, and describe the features that make it successful.

**Core Idea ETS2**

**Links Among Engineering, Technology, Science, and Society**

How are engineering, technology, science, and society interconnected?

New insights from science often catalyze the emergence of new technologies and their applications, which are developed using engineering design. In turn, new technologies open opportunities for new scientific investigations. Together, advances in science, engineering, and technology can have—and indeed have had—profound effects on human society, in such areas as agriculture, transportation, health care, and communication, and on our natural environment. Each system can change significantly when new technologies are introduced, with both desired effects and unexpected outcomes.

**ETS2.A: Interdependence of Science, Engineering, and Technology**

What are the relationships among science, engineering, and technology?

The fields of science and engineering are mutually supportive, and scientists and engineers often work together in teams, especially in fields at the border of science and
Together, advances in science, engineering, and technology have—and indeed have had—profound effects on human society.

Engineering, advances in science offer new capabilities, new materials, or new understanding of processes that can be applied through engineering to produce advances in technology. Advances in technology, in turn, provide scientists with new capabilities to probe the natural world at larger or smaller scales to record, manage, and analyze data; and to model ever more complex systems with greater precision. In addition, engineers’ efforts to develop or improve technologies often raise new questions for scientists’ investigations.

Grade Band Endpoints for ETS2.A

By the end of grade 3. People encounter questions about the natural world every day. There are many types of tools produced by engineers that can be used in science to help answer these questions through observation or measurement. Observations and measurements are also used in engineering to help test and refine design ideas.

By the end of grade 5. Tools and instruments (e.g., rulers, balances, thermometers, graduated cylinders, telescopes, microscopes) are used in scientific exploration to gather data and help answer questions about the natural world. Engineering design can develop and improve such technologies. Scientific discoveries about the natural world can often lead to new and improved technologies, which are developed through the engineering design process. Knowledge of relevant scientific concepts and research findings is important in engineering.

By the end of grade 8. Engineering advances have led to important discoveries in virtually every field of science, and scientific discoveries have led to the development of entire industries and engineered systems. In order to design better technologies, new science may need to be explored (e.g., materials research prompted by desire for better batteries or solar cells, biological questions raised by medical problems). Technologies in turn extend the measurement, exploration, modeling, and computational capacity of scientific investigations.

By the end of grade 12. Science and engineering complement each other in the cycle known as research and development (R&D). Many R&D projects may involve scientists, engineers, and others with wide ranges of expertise. For example, developing a means for safely and securely disposing of nuclear waste will require the participation of engineers with specialties in nuclear engineering, transportation, construction, and safety; it is likely to require as well the contributions of scientists and other professionals from such diverse fields as physics, geology, economics, psychology, and sociology.

ETS2.B: INFLUENCE OF ENGINEERING, TECHNOLOGY, AND SCIENCE ON SOCIETY AND THE NATURAL WORLD

How do science, engineering, and the technologies that result from them affect the ways in which people live? How do they affect the natural world?

From the earliest forms of agriculture to the latest technologies, all human activity has drawn on natural resources and has had both short- and long-term consequences, positive as well as negative, for the health of both people and the natural environment. These consequences have grown stronger in recent human history. Society has changed dramatically, and human populations and longevity have increased, as advances in science and engineering have influenced the ways in which people interact with one another and with their surrounding natural environment.

Science and engineering affect diverse domains—agriculture, medicine, housing, transportation, energy production, water availability, and land use, among others. The results often entail deep impacts on society and the environment, including some that may not have been anticipated when they were introduced or that may build up over time to levels that require attention. Decisions about the use of any new technology thus involve a balancing of costs, benefits, and risks—aided, at times, by science and engineering. Mathematical modeling, for example, can help provide insight into the consequences of actions beyond the scale of place, time, or system complexity that individual human judgments can readily encompass, thereby informing both personal and societal decision making.

Human populations and longevity have increased, as advances in science and engineering have influenced the ways in which people interact with one another and with their surrounding natural environment.
Not only do science and engineering affect society, but society’s decisions (whether made through market forces or political processes) influence the work of scientists and engineers. These decisions sometimes establish goals and priorities for improving or replacing technologies; at other times they set limits, such as in regulating the extraction of raw materials or in setting allowable levels of pollution from mining, farming, and industry.

**Grade Band Endpoints for ETS2.B**

**By the end of grade 2.** People depend on various technologies in their lives; human life would be very different without technology. Every human-made product is designed by applying some knowledge of the natural world and is built by using materials derived from the natural world, even when the materials are not themselves natural—for example, spoons made from refined metals. Thus, developing and using technology has impacts on the natural world.

**By the end of grade 3.** Over time, people’s needs and wants change, as do their demands for new and improved technologies. Engineers improve existing technologies or develop new ones to increase their benefits (e.g., better artificial limbs), to decrease known risks (e.g., seatbelts in cars), and to meet societal demands (e.g., cell phones). When new technologies become available, they can bring about changes in the way people live and interact with one another.

**By the end of grade 5.** All human activity draws on natural resources and has both short- and long-term consequences, positive as well as negative, for the health of both people and the natural environment. The uses of technologies and any limitations on their use are driven by individual or societal needs, desires, and values; by the findings of scientific research; and by differences in such factors as climate, natural resources, and economic conditions. Thus technology use varies from region to region and over time. Technologies that are beneficial for a certain purpose may later be seen to have impacts (e.g., health-related, environmental) that were not foreseen. In such cases, new regulations on use or new technologies (to mitigate the impacts or eliminate them) may be required.

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*Dimension 3: Disciplinary Core Ideas—Engineering, Technology, and Applications of Science*

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Engage with Engineering: Preparing a Science Department to Integrate Engineering Practices into its Courses

Amy Winston
Department Head, Science and Technology/Engineering
Newton North High School
www.tigerscience.us

Tigerscience: The Newton North Science Department

Newton North High School  
Science and Technology/Engineering Department  
457 Walnut Street  
Newtonville, MA 02460

The Science and Technology/Engineering Department strives for all students to attain scientific literacy - a basic understanding of the natural sciences, mathematics, technology, and their interactions. To graduate from Newton North High School, a student must successfully earn 6 credits through physical science courses and 5 credits through biological science courses. While the graduation requirement is two years, most colleges require at least three years of high school science. We recommend that all students take Introductory Physics in the 9th grade, Chemistry in the 10th grade, and Biology in the 11th grade. The department head must approve deviations from this sequence.

Department Head:  
Ms. Amy Winston  
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Agenda

Why

Where

What

How
Opportunities

Engineering

Science
## Framework Practices

<table>
<thead>
<tr>
<th>Scientific Inquiry</th>
<th>Engineering Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ask a question</td>
<td>Define a problem</td>
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<tr>
<td>Obtain, evaluate and communicate technical information</td>
<td>Obtain, evaluate and communicate technical information</td>
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<tr>
<td>Plan investigations</td>
<td>Plan designs and tests</td>
</tr>
<tr>
<td>Develop and use models</td>
<td>Develop and use models</td>
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<tr>
<td>Design and conduct tests of experiments or models</td>
<td>Design and conduct tests of prototypes or models</td>
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<tr>
<td>Analyze and interpret data</td>
<td>Analyze and interpret data</td>
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<tr>
<td>Use mathematics and computational thinking</td>
<td>Use mathematics and computational thinking</td>
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<tr>
<td>Construct explanations using evidence</td>
<td>Design solutions using evidence</td>
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<tr>
<td>Engage in argument using evidence</td>
<td>Engage in argument using evidence</td>
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</tbody>
</table>
Turn to a neighbor

Which part of the "why" is most compelling in your context?
Where?

NNHS Context
Demographics

- 2000 students
- White – 70%
- First Language not English – 16%
- Low Income – 16%
- Special Education – 25%
- High Needs – 36%
- Post-Secondary Education: 91%
Science Program

Science

- 24 science teachers
- Physics – Chem – Bio
- 2 year Graduation Req
Engineering Timeline

1995
- Tech/Engineering Program
- CVTE

2007
- Engineering = Science + CVTE
- 1 Engineering Teacher

2011
- Start to think about Infusion

2014
- 4 Engineering Teachers
- 3 Full Sequences of Courses
<table>
<thead>
<tr>
<th>NNHS Engineering Courses</th>
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</thead>
<tbody>
<tr>
<td><strong>Greeneering</strong></td>
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<tr>
<td>Xplore</td>
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<tr>
<td>Greeneering 1 &amp; 2</td>
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<tr>
<td>Greeneering 101</td>
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<tr>
<td>Greeneering 201</td>
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<tr>
<td>Greeneering 301</td>
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<tr>
<td><strong>Robotics</strong></td>
</tr>
<tr>
<td>Robotics 1</td>
</tr>
<tr>
<td>Robotics 2</td>
</tr>
<tr>
<td>Honors Robotics 3</td>
</tr>
<tr>
<td><strong>Engineering Tech</strong></td>
</tr>
<tr>
<td>Exploring Tech 1 &amp; 2</td>
</tr>
<tr>
<td>Fashioning 1 &amp; 2</td>
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<tr>
<td>Engineering Technology</td>
</tr>
<tr>
<td>Engineering 1 &amp; 2</td>
</tr>
<tr>
<td>Honors Engineering 3</td>
</tr>
<tr>
<td><strong>Advanced Exploratory</strong></td>
</tr>
<tr>
<td>Introductory</td>
</tr>
</tbody>
</table>
Turn to a neighbor

How is your context similar to NNHS? How is your context different?
What?

- **Science teachers who**
  - feel comfortable with the engineering design process
  - have introductory engineering content knowledge.
  - integrate engineering practices and content into their science classes.

- **ALL students**
  - being exposed to engineering ideas.
  - seeing engineering as an opportunity.
External PD

Courses

Partnerships

Externships
Internal PD

- Identify the "Why"
- Experiences
- Content Knowledge
- Highlight Existing Examples
- The Future
Marshmallow Challenge
Setting the Context

Identify the Why
Experiences
Mini-Activities

- Diving Into the Practices.
- NGSS Infusion

- Let’s Jigsaw
  - Left: Practices and Right: Infusion
  - Read through your mini-activities and then talk to a neighbor about them. What do you think? How could you use them in your context.
  - Get up and talk to someone from the other side of the room. Share with each other what your thoughts are about the mini-activities.
K-12 Framework Jigsaw
Change in Practice Protocol

- Essential Question: Where do engineering practices (EDP) currently exist? Where can they exist?
  - Preparation
  - Individual Presentation
  - Group Processing
  - Gallery Walk

Highlight Existing Examples and The Future
Tips

• "Engineering Content Knowledge" and "Engineering Pedagogical Content Knowledge"

• Start every PD Session by acknowledging the anxiety.

• Place the PD in context.