



Integrating Engineering Practices Into K–12 Instruction

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Introduction

Providing students with the emotional and intellectual tools necessary to persevere in the face of difficulty or failure is a primary concern for K–12 teachers. A growing body of research suggests that developing a growth mindset among students, as opposed to a fixed mindset, can help set the stage for academic endurance. In sum, a growth mindset describes the belief that talent can be developed and expanded through hard work and helpful input from others, whereas a fixed mindset describes the belief that every individual has an innate and static ability level.

According to Carol Dweck, a pioneer in growth mindset research, the cultivation of one mindset or the other leads students to view their schoolwork as either an opportunity to show off their natural ability or an opportunity to acquire a new ability (Kravovsky, 2007). Students who view academic tasks as a measure of their self-worth tend to avoid challenges and give up, or even regress, when faced with a setback. Students who view academic tasks as a chance to acquire knowledge and skill are more likely to seek challenges and persevere through setbacks.

The question facing educators is how to utilize our understanding of the growth mindset in a manner that will position our students for success in school and in future careers. Indeed, many prominent companies, especially in the technology sector, have embraced growth mindset research and training as a means of building an energized and innovative workforce (Dweck, 2016). Fortunately, researchers agree that a growth mindset can be taught and acquired through pedagogical methods that emphasize the fluid nature of intelligence and take a positive view of failure as a necessary part of learning. This can be accomplished through the integration of the engineering practices identified by the National Research Council (NRC) in its Framework for K–12 Science Education.

The NRC Framework highlights eight engineering practices that are crucial to the modern vision of science education. Those practices are: (1) Ask Questions and Define Problems; (2) Develop and Use Models; (3) Plan and Carry out Investigations; (4) Analyze and Interpret Data; (5) Use Mathematics and Computational Thinking; (6) Construct Explanations and Design Solutions; (7) Engage in Argument from Evidence; and (8) Obtain, Evaluate, and Communicate Information (Appendix D).

The pedagogical shift portended by the NRC Framework promises to nurture a new generation of students who engage with science on a concrete level and are capable of making beneficial, practical use of their science lessons both inside and outside of the classroom.

Engineers are specialists in solving problems that require unique and complex solutions. As such, they are trained to nurture habits of mind that foster one's ability to engage in divergent thinking (Appendix B Convergent/Divergent Thinking and Task Samples) and to respond positively to setbacks. These habits of mind, which include systems thinking, creativity, communication, collaboration, and ethical considerations, provide a foundation upon which a student can begin to master engineering practices. By learning to think like an engineer and employ engineering practices, students will begin to approach challenges with a growth mindset and vastly expand their problem-solving toolkit.

As science education continues to evolve and improve, students' understanding of core disciplinary ideas will be evaluated in tandem with their ability to use scientific and engineering techniques and practices as they engage with both the natural and human designed world. Teaching students about engineering practices, and giving them the tools to apply these practices, will position them for success.

While each of the NRC practices describes a relatively simple concept, the key for educators will be figuring out how to get students to internalize these lessons and developing a sense of what this will look like in the classroom. The following pages contain information and recommendations intended to help teachers create vibrant, enthusiastic classrooms in which the eight engineering practices can be incorporated in a thoughtful and strategic manner.

Classroom Environment

Students often decide what to expect from a class based on the appearance and layout of the room in which it is taught. How a classroom is configured can facilitate the mode of learning that corresponds to the pedagogical style of the teacher. Setting up and decorating your classroom in a manner that supports your goals and processes for the year is an excellent opportunity to set a positive tone from the very first moment students enter the room.

A modern science classroom should emphasize and support the changing mode of science education. One simple and effective tool for introducing students to the eight engineering practices is to prominently display them on the wall. Students will be naturally curious about the terms and will also be able to look to them as a reference throughout the year. Utilizing engineering practices will be a new concept for most students and these visual reminders not only help students to remember the practices but also underscore their importance.

Posters illustrating the distinctions between growth and fixed mindsets and convergent versus divergent thinking can also help students internalize instructional shifts. In particular, it helps them understanding that science is about processes and not just information. Students should be encouraged to incorporate new terms and concepts into their formal and informal communications whenever possible.

One final suggestion is to have a “famous failures wall” dedicated to noteworthy mistakes and mishaps. A willingness to fail, and to learn from failure, is of utmost importance in process-based science education. Remember, our educational system has historically conditioned most students to associate failure with negative outcomes and consequences (e.g., low grades or penalties). A famous failures wall can go a surprisingly long way toward establishing a culture of growth mindset in your classroom, especially if it is light and amusing. It can even be a fun idea to memorialize student failures throughout the year. The point, of course, is not to ridicule or tease students, but to remind them that mistakes, accidents, and failed models are integral to problem solving and innovation.

Engineering Practices in Pedagogy

Pedagogy is said to comprise three complementary concepts: curriculum, instruction, and assessment. Each of these three concepts will be enhanced by the consistent utilization of engineering practices and the cultivation of a growth mindset in the classroom.

In the past, science education focused on the acquisition of information in and around specific topics. Different areas of science (e.g., engineering, technology & the application of science; and earth, life & space, and physical sciences) were typically separated into academic silos. The new science pedagogy is more flexible. It emphasizes the importance of creativity, collaboration, and productive struggle in a project-based learning environment. Teachers increasingly embrace crosscutting concepts as an instructional technique and problem-solving tool. The performance of students is assessed based on the understanding and application of processes in addition to their mastery of core disciplinary ideas.

When shifting their approach to instruction, teachers must also prepare students for a new type of learning experience. The best way to fully engage students with the new science pedagogy is to be overt about explaining the changes they can expect in terms of classroom activities and discussions. To that end, curriculum should begin with a unit that familiarizes students with engineering practices and builds a common, problem-solving vocabulary.

Teachers can start to shift their students' mindsets with a series of smaller, group tasks designed to highlight the engineering practices and positive habits of mind. For example, student groups could take part in the "Spaghetti Marshmallow Tower Challenge." This challenge asks students to support a marshmallow at the greatest possible height using only a limited supply of dry pasta and tape. When they are finished, students will reflect upon their group's process and whether they displayed or did not display specific practices and habits of mind. Students could be given a reflection chart or asked discussion questions, such as:

- "How did the group respond to new ideas?"
- "Did any members of the group proffer a particularly unique or creative idea?"
- "Did your group conceive of the tower as one large entity or as smaller systems that interacted to form the whole?"
- "Which of the eight practices were relevant to this project?"
- "If you could do the project a second time, what changes would you make to your decision-making and building processes?"

The goal here is to inspire students to become aware of their conditioned thinking and communication patterns, so that they can begin to approach the curriculum (and the world at large) with engineer-colored glasses and a growth mindset that embraces productive struggle. As tasks become more involved and students become more comfortable with the common problem-solving tools and vocabulary, discussion and review questions can be expanded to reach more complex areas, such as the ethical or economic requirements of an acceptable solution to a problem.

The mode of instruction in science education will also undergo adjustments so that it can best complement the modern ethos and curriculum. Formerly, the learning and doing phases of science were largely separate. Many current teachers will remember that their science teachers lectured from the front of the classroom on Monday through Thursday. They were usually given a lab assignment on Friday that asked them to demonstrate or expand upon the principles they learned throughout the week. In that model, lab assignments typically had a correct or desired outcome.

The modern science classroom promotes a shifting instructional paradigm in which teachers move from being a “sage on the stage” to a “guide on the side.” Memorization and correct answers make way for creativity and engagement with effective practices. Experimental Design and Engineering Design are two process-driven approaches to teaching and learning that incorporate multiple practices into the context and sequence of a single thematic. This “bundling” of practices offers students multiple opportunities to demonstrate that they are effectively engaging with the content.

Teachers will find that the best way to get students to engage with the new curriculum is to use an instructional style in which they serve as a facilitator of engineering practices and model a growth mindset for the students. Some students lose interest in science when they understand it to be a non-creative endeavor. Encourage boldness and creativity by rewarding interesting or unique problem-solving ideas.

If an idea is unsuccessful, make clear that redesign is more important than design in the final outcome. Regardless of whether an initial idea is wildly successful or a complete failure, first attempts should always be viewed as part of the learning process. The most important skill to be acquired in science class is not the ability to demonstrate one’s intelligence by solving a problem on the first try, but the ability to think critically and creatively about a proposed solution so that it can be developed to its fullest potential.

Students should engage in productive struggle whenever possible. The process of designing, modeling, testing, analyzing, and redesigning a solution to a problem is where productive struggle occurs. Fighting through the challenges inherent to this process is what allows for the birth and execution of great ideas.

It should be clear to students that even if they build a wildly successful balloon-powered vehicle or marshmallow tower on their first try, they will still be required to evaluate and improve upon their design. Their ability to do so will be reflected in the assessment of their performance. Likewise, a naturally gifted student who designs the tallest tower in the class while largely shutting out input and participation from her group members must understand that her assessment will include an evaluation of how she engaged with and performed within the group.

Engineering Notebooks and Evidence Statements

Initially, some teachers may have difficulty revising their assessment standards and practices to fit a new curriculum and instructional method. Two tools, engineering notebooks and evidence statements, can help them address abstract concepts like productive struggle and engagement with engineering habits and practices. Engineering notebooks and evidence statements should be adopted in every science classroom to provide educators with concrete information about each student's mastery of the course material in a form that goes beyond traditional testing.

The term engineering notebook refers, not surprisingly, to a notebook kept by engineers and their teammates during the course of a project. These logs are the most crucial piece of evidence or documentation in a patent application process, and/or the defense of intellectual property. A student's engineering notebook can be highly structured or completely open-ended, but the purpose of it is to create a record of the student's contemporaneous thought processes and retrospective reflections as they work through a problem or task.

Thoughts and reflections recorded in an engineering notebook should explicitly reference the eight engineering practices. Students should use headers for each section of their notebook, such as "Identification of the problem" before a section in which students record data or "Requirements for a solution" as he or she begins the design and modeling process. Reflections can be done at the end of each class session or at the end of the week and should prompt students to think in a critical and self-aware manner about how they or their group approached a task.

Evidence statements are a specific tool by which teachers and students can demonstrate that they met certain performance standards. An effective evidence statement will clearly state a performance expectation that is cast in the terminology of the eight practices and the common problem-solving vocabulary established in the classroom. Students should provide concrete and concise examples of how they met the applicable standard.

NGSS recommends that evidence statements include three dimensions: a science or engineering practice, disciplinary core idea, and crosscutting concepts (models are available at nextgenscience.org). The inclusion of these three dimensions will stimulate student understanding of the value of the eight practices in learning and practicing science.

Conclusion

The NGSS provide an excellent framework through which science education can evolve from traditional core disciplinary ideas into a more holistic, engaging, and practical study. The paradigm shift in science education aims to create self-aware, critical thinkers who understand that positive results in the real world are born from a growth mindset and persistent engagement with the design process.

By incorporating engineering practices and habits of mind into the classroom, teachers can mold students who embrace productive struggle, work through problems with creativity, and use evidence-based, problem-solving skills to push their ideas further. This approach promises to instill students with a passion for improving their world through science.

Works Cited

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Appendices

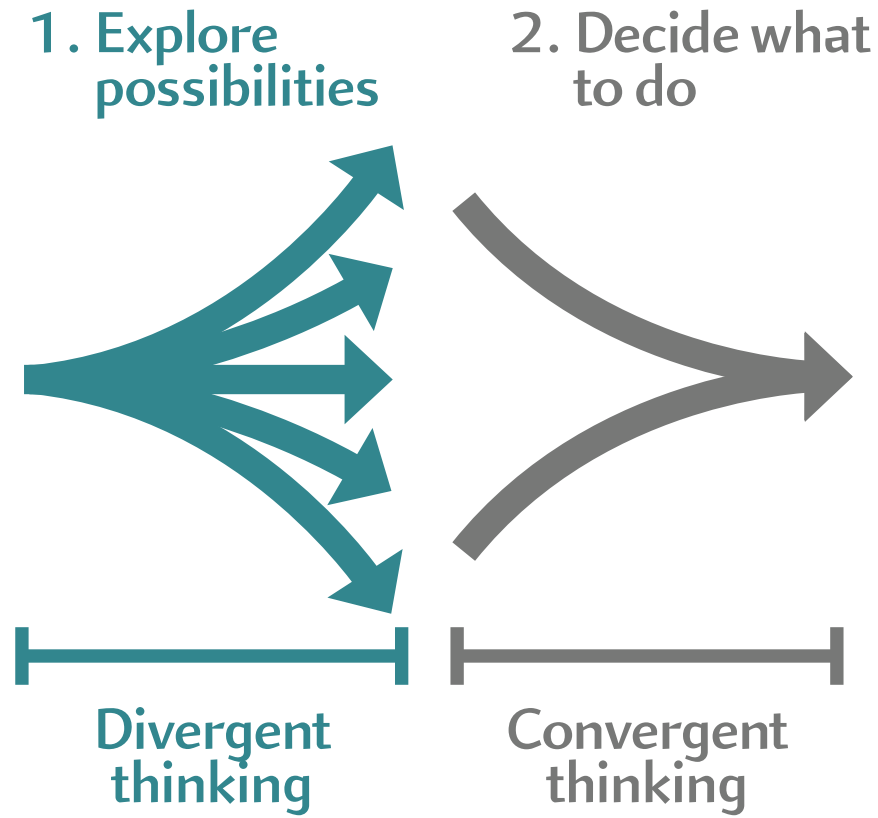
Appendix A

Fixed Mindset vs. Growth Mindset

Fixed Mindset	Growth Mindset
<ul style="list-style-type: none">▪ Successes and failures are reflections of my aptitude	<ul style="list-style-type: none">▪ Successes and failures are reflections of my effort and execution
<ul style="list-style-type: none">▪ Intelligence and ability are static characteristics	<ul style="list-style-type: none">▪ Intelligence and ability are fluid characteristics that can be cultivated through hard work and open-mindedness
<ul style="list-style-type: none">▪ I do not take part in activities that do not come easily to me	<ul style="list-style-type: none">▪ I enjoy being challenged because it gives me a chance to learn and grow
<ul style="list-style-type: none">▪ If I have difficulty completing a task it is because I lack ability in that area	<ul style="list-style-type: none">▪ Challenging tasks increase my resolve and encourage me to work harder and explore new approaches
<ul style="list-style-type: none">▪ Challenging tasks cause me to grow frustrated and give up	<ul style="list-style-type: none">▪ Every time I struggle through a task I become smarter and more capable
<ul style="list-style-type: none">▪ I become defensive when given negative feedback	<ul style="list-style-type: none">▪ I appreciate honest feedback
<ul style="list-style-type: none">▪ Natural talent is a more valid path to success than hard work	<ul style="list-style-type: none">▪ The only path to success is hard work and a positive attitude

Appendix B

Convergent vs. Divergent Thinking



Divergent Thinking Task Samples

Instructions:

For either of the tasks below, see how many answers you can generate within the given time constraint:

Option A

Socks are something most people use on their feet, fulfilling the needs for warmth, protection, or even fashion. However, a sock can also be used to solve other problems or satisfy different needs and wants—especially if you found yourself in a jam with limited resources. How many other uses for a sock can you think of? Start by thinking about the form, function, and composition of an ordinary pair of socks. Consider how those attributes may be valuable or serve an alternative function/purpose. List your answers below or on an extra piece of paper.

Option B

Cars are used to transport people and goods from one place to another. While cars come in many different colors, the colors we use on vehicles can change depending on what is being transported! Could you imagine a world where you didn't have a choice? What if we painted every vehicle on the roads with the same color yellow? How would it affect society? List as many potential outcomes as you can for each category (use more paper if needed):

Problems (negative outcomes)	Opportunities (negative outcomes)

Appendix C

Engineering Habits of Mind

Engineering habits of mind include:

1. Systems Thinking
2. Creativity
3. Optimism
4. Collaboration
5. Communication
6. Ethical considerations

Appendix D

NGSS Practices of Science & Engineering

1. Ask Questions and Define Problems

The initial task in problem solving is to establish a clear definition of the problem. A satisfactory definition of a problem will include consideration of factors such as the scope of the problem, specific circumstances that must be addressed by an eventual solution, and any constrictions that are likely to be encountered. This practice should encourage students to think creatively about the problem and to investigate as many angles as possible. The engineering habits of mind, especially creativity and ethical thinking, can be useful prompts for getting students to ask interesting questions that frame the problem in stimulating terms.

2. Develop and Use Models

“Models” is a broadly defined term and can refer to diagrams, charts, simulations, or physical replicas that are useful in describing a system or idea. Models can be used to test a design for flaws, communicate a concept or design, compare predictions to actual results, or evaluate the performance of a proposed solution.

For younger students, modeling may take the form of basic mechanical drawings, but as their abilities progress they will be able to perform tasks like diagramming data sets to describe natural phenomena or demonstrate the effect of new stimuli on a system. Modeling is crucial for any aspiring scientist or engineer. Students should also learn to evaluate models, so that those models can be modified as needed to produce more accurate results or accommodate unexpected data.

Modeling is a labor-intensive process that requires attention to detail and a willingness to make adjustments and respond positively to failure. Failure is built into the modeling process, so focusing on this practice can help students grow accustomed to approaching their work with a growth mindset. In fact, failure is a very important part of the modeling process, because failures that occur in a model can be prevented when the stakes are much higher. It is certainly preferable to discover a structural flaw in a model bridge than in a real one!

3. Plan and Carry Out Investigations

Students should be encouraged to carry out investigations at every level of their K–12 education. Ideally, these investigations will range from those suggested by a teacher to those that arise from the student’s own questions (NRC Framework, 2012, p. 61).

Investigations should have a clear purpose and utilize methodology that generates data to support or cast doubt upon a predicted outcome. In teaching students to plan and carry out investigations, there should be an expectation that their methods will become more systematic and specific over time, whether the tools and subject of their investigation is in the field or the laboratory.

It is important to note that the eight engineering practices are complementary and overlapping. For example, the process of planning and carrying out an investigation will necessarily require the students to ask questions, develop models, and obtain and evaluate data.

4. Analyze and Interpret Data

The analysis and interpretation of data is a fundamental skill for any scientist or engineer. Raw data is generally unruly, disorganized, and unusable until it is distilled into a productive format. Through the course of their K–12 science education, students should continually increase their toolkit for analyzing and interpreting data. This process will be most interesting to students when they understand that analysis and interpretation of data allows for, and is improved by, creativity. After all, the core purpose of analyzing and interpreting data is to turn raw material into something that can be readily communicated to others and evaluated. This process is how a massive list of measurements of the beak sizes of finches in the Galapagos can be transformed into a chart, how that chart can give rise to a narrative about beak sizes being affected by the relative severity of storms and droughts, and that narrative can explain the diversity of species. Again, encouraging creativity in this practice can help inspire students to fully engage with the material.

5. Use Mathematics and Computational Thinking

In the modern world math, science, and engineering all rely heavily upon the use of computers and digital technology. Accordingly, students must have a basic proficiency in computational thinking to capture and interpret vast data sets and to perform high level calculations. At its core, this practice is about acknowledging the fact that mathematics and technology are inextricably integrated into science and engineering as tools for the collection and interpretation of data as well as media for the communication of ideas. Wherever possible, technology should be incorporated into the classroom so that students will be comfortable using algorithms, functions, and computational models.

6. Construct Explanations and Design Solutions

This practice represents a synthesis of science and engineering goals in that scientists endeavor to construct explanations for the causes of phenomena and engineers endeavor to design solutions to problems (Next Generation Science Standards, Appendix F, p. 11, 2013). By integrating the goals of science and engineering into a single practice, the Framework is presenting a vision of science education that goes beyond the scientific method and seeks to stimulate students by providing a window through which they can see how their studies may affect and improve the real world. Rather than simply finding an evidence based explanation for a phenomenon, modern science students will commonly be asked to apply that evidence based explanation in service of problem solving practices. The core notion here is that engineering practices can benefit our conception of scientific principles and vice versa.

7. Engage in Argument from Evidence

If asked to list the skills traditionally attributed to a scientist, few students would mention argument. However, there is an extent to which scientific study is, in truth, entirely about argument. Science is about constructing explanations and finding correct answers, and the process by which a hypothesis or theory is tested involves advocating for or against a proposition using logic and evidence. Of course, argument in science and engineering ideally serves a different purpose than argument in philosophy or law. Instead of arguing to prove that superiority of one's own position, the purpose of scientific argument is to find a correct answer. Counterpoints and contrary evidence should not be dismissed or attacked, but understood and incorporated where possible so that ideas can be compared and evaluated honestly on their merits. Emphasizing the engineering habits of mind will help to prevent scientific argument from devolving into a battle of egos.

8. Obtain, Evaluate, and Communicate Information

The new science pedagogy has a decidedly holistic bent and attributes an increased value to language skills. The ability to absorb new ideas, argue and evaluate a hypothesis or design solution, and communicate information are all valuable skills for a scientist or engineer. Scientific ideas are commonly obtained, evaluated, and communicated through tables, charts, diagrams, etc., but this process also occurs through conversation, articles, and journalism. In the modern media landscape, scientific ideas are more likely than ever to be submitted to the court of public opinion so the ability to make a compelling presentation of information is growing ever more important. In the classroom, crafting a compelling narrative about a problem or a design solution can help students to relate to the material and be stimulated by it. The evaluation prong of this practice should be understood to include information literacy in addition to the more traditional scientific practice of analyzing data. Digital media has given rise to an abundance of readily available sources, so the ability to compare different sources and assess their reliability is an important skill. Students should be able to review citations and think critically about the way in which a source collects and employs data.