Teacher's Guide to Using Engineering Design in Science Teaching and Learning

High School Edition

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Objective - to further the implementation of the Engineering Design portion of the Science Standards in Oregon classrooms and improve teachers' effectiveness at teaching science.

Why this Guide Exists

A change is coming – Educators in many states are discovering that engineering is a great way to support, improve and enhance the teaching of science. Oregon started riding this wave in 2009 when it added Engineering Design as one of four core standards in its Science Standards. Using the Engineering Design process gives teachers an additional way to succeed with 21st Century students. It can lead to increased student retention, engagement and confidence. This guide will help teachers use Engineering Design to reinforce science content in the classroom.

Oregon is one of 26 states providing leadership in the Next Generation Science Standards (NGSS) development process. Oregon has shown a strong commitment to standards-based learning through its adoption of the Common Core State Standards (CCSS). Oregon's current standards are based on some of the same research that underlies the ongoing development of the NGSS.

http://cicobb.typepad.com/es/2012/05/index.html

http://www.achieve.org/ngss-states

Because Engineering Design is in the Oregon standards and engineering practices will be in the NGSS, the time is right for Oregon to use the Engineering Design process to teach science alongside the Scientific Inquiry process. Incorporating Engineering Design will not only benefit Oregon students immediately it will help prepare Oregon teachers for what's coming next – the Next Generation Science Standards.

Overview and Introduction

Goals of the Guide

This guide was developed in collaboration between the Industry Partnerships Department of the Oregon University System and the Oregon Department of Education (“ODE”) to further the implementation of the Engineering Design portion of the Oregon Science Content Standards (the ‘Standards”) in classrooms and improve teachers’ effectiveness at teaching science.

The NGSS take engineering design further by including Scientific and Engineering Practices:

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics, information and computer technology, and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information.

While this primer focuses on Oregon’s current standards, it also anticipates the NGSS’s use of scientific and engineering practices.

Oregon Science Content Standards

The Oregon Science Content Standards define the scientific content, knowledge, and process skills that all Oregon students are expected to learn during science instruction in K-8 and high school. The adopted science content standards include four core standards at each grade from kindergarten through eighth grade and for high school. These core standards provide the major unifying concepts and processes that will be the primary focus of teaching and learning across the grades. Underneath each of these core standards are from one to seven content standards, which provide the details necessary for instruction and assessment.

Since 2009, the Standards have included Engineering Design as a core Science Process Skill. In the context of the Standards, the term **Engineering Design describes the concept of using the application of scientific principles to everyday problems**. Engineering Design is a key skill

Overview and Introduction

and describes what students should know about how engineers use science as well as providing a way for students to learn about science in addition to Scientific Inquiry.

Scientific Inquiry Process & Engineering Design Process

Within Oregon's *Science Standards Framework: The big ideas organized by science discipline and core strand*, Scientific Inquiry and Engineering Design are both considered Science Process Skills. Students use inquiry-based science when they apply scientific reasoning and critical thinking to support conclusions or explanations with evidence from their investigations and students use the engineering design process when they define problems and design solutions to support conclusions or explanations with evidence from their investigations.

Dimensions of Scientific Inquiry	Dimensions of Engineering Design
1. Articulate Questions	1. Define Problems
2. Investigate	2. Design
3. Discover Scientific Knowledge	3. Create or Refine Technological Solutions
4. Communicate and Apply	4. Communicate and Apply

Overview and Introduction

Oregon Engineering Design Core and Content Standards

Grades	Core Standard	Engineering Design Content Standards
9-12	Engineering design is a process of formulating problem statements, identifying criteria and constraints, proposing and testing possible solutions, incorporating modifications based on test data, and communicating the recommendations.	• Define a problem and specify criteria for a solution within specific constraints or limits based on science principles. Generate several possible solutions to a problem and use the concept of trade-offs to compare them in terms of criteria and constraints. • Create and test or otherwise analyze at least one of the more promising solutions. Collect and process relevant data. Incorporate modifications based on data from testing or other analysis. • Analyze data, identify uncertainties, and display data so that the implications for the solution being tested are clear. • Recommend a proposed solution, identify its strengths and weaknesses, and describe how it is better than alternative designs. Identify further engineering that might be done to refine the recommendations. • Describe how new technologies enable new lines of scientific inquiry and are largely responsible for changes in how people live and work. • Evaluate ways that ethics, public opinion, and government policy influence the work of engineers and scientists, and how the results of their work impact human society and the environment.

Oregon Essential Skills

Beginning in 2012, Oregon students must demonstrate proficiency in identified Essential Skills. These are 21st century skills needed for success in college, the workplace, and civic life. The State Board of Education approved three assessment options for students to demonstrate Essential Skill proficiency: (1) OAKS state test, or (2) local assessments consistent with state criteria, or (3) other approved standardized tests (e.g. SAT, PLAN, ACT, PSAT, Work Keys, COMPASS, ASSETT).

Students who use Engineering Design to learn science will also be building essential skills. By the very nature of engineering design, students will be required to **read** and comprehend a variety of text, **write** clearly and accurately, and to apply **mathematics** to projects outside of their math textbook. Engineering design requires students to listen actively, speak clearly and coherently (team-based projects), think critically and analytically, and often to use technology such as a computer and computer software to help solve a problem. If students focus on solving problems to make a better world, they will also be developing the essential skills of demonstrating civic and community engagement and global literacy.

Overview and Introduction

Essential Skills Required for Graduating Class**	Essential Skills to be Phased-In Over Subsequent Years
2012: Read and comprehend a variety of text 2013: Write clearly and accurately 2014: Apply mathematics in a variety of settings **Revised ES timeline adopted by the State Board Aug. 2009.	• Listen actively and speak clearly and coherently • Think critically and analytically • Use technology to learn, live, and work • Demonstrate civic and community engagement • Demonstrate global literacy • Demonstrate personal management and teamwork skills

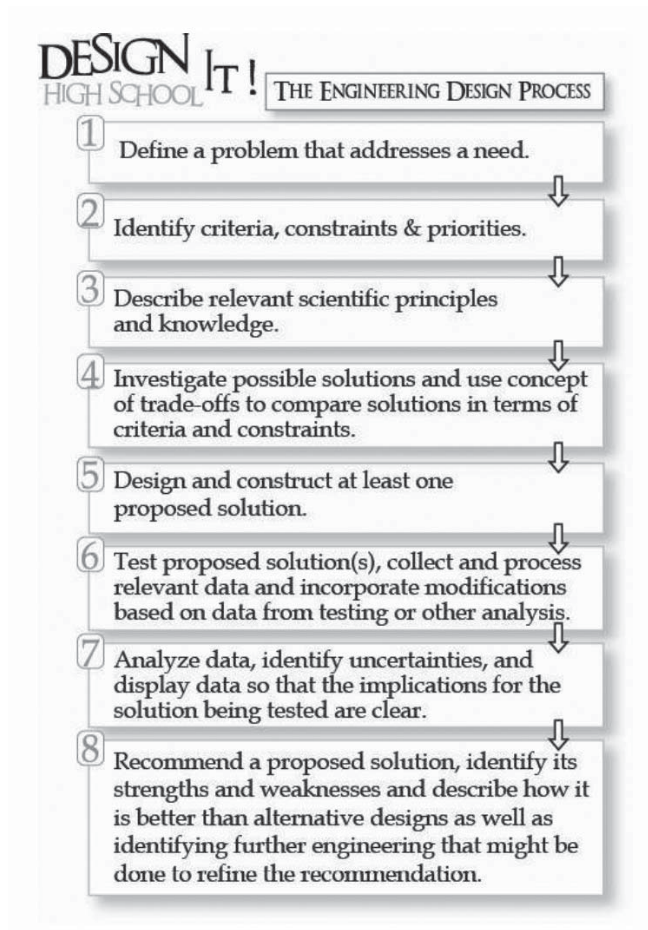
Next Generation Science Standards

Twenty-six states, including Oregon, participated in the development of the Next Generation Science Standards. According to Leslie Payne of the American Society of Civil Engineers, "The framework for the new standards emphasizes first and foremost the new vision that K-12 science education should reflect real world interconnections in science, including active engagement in scientific AND engineering practices, and the application of intersecting concepts to improve understanding of core ideas. Perhaps most important is the idea that scientific and engineering practices should be included in learning experiences that span student's educational development from the very beginning of their school years. This is a major departure from previous standards that did not integrate scientific principles, engineering application or core concepts from the various disciplines of science learning."

Why use the Engineering Design Process?

Motivating Students to Learn Science

One positive aspect of using the Engineering Design process is that students begin to look at problems, issues and constraints from multiple viewpoints and in relationship to an assortment of situations and scenarios. New problems may arise from one solution, and those problems may lead to new ideas and solutions. There are also usually several different solutions to each problem. A solution may be designed for a particular audience (a passenger van to transport a large family) or it may be more general (a vehicle that can carry up to 5 people). Both solutions work for the problem of transporting people from point A to point B. Good engineering design considers people's needs (gas mileage, size of people or cargo, time spent in the vehicle, etc) to determine the best solution.



By solving problems that consider the needs of people, the doors to creativity open wide and **student engagement** increases. As students build skills in using Engineering Design to learn science, they no longer need to sit back and wait for instructions. Instead, they explore, create, design, innovate, imagine, test and evaluate their solutions. The advantages of using Engineering Design to teach science are similar to using Scientific Inquiry: students see connections to the world around them at the same time they develop problem solving skills that they can use in school and throughout their life.

By using this process, students learn that engineering design, like life itself, is an endless process of solving problems. In dealing with life's many challenges, successful adults take the same steps as the ones that students will use in their engineering design experiences such as stating the problem clearly, collecting information, developing possible solutions, selecting the best solutions, implementing the solution, evaluating the solution, making needed changes and improving the solution, and then communicating their findings.

As a society we need to accept math, technology and science as tools to understand the world and solve problems. To motivate and inspire students, educators need to provide

Why use the Engineering Design Process?

exposure, awareness, meaningful interactions, curricula, content, relevance to success, “aha” moments, and sustained engagement leading to a student’s interest in learning more about science and possibly pursuing a degree in science or engineering. Positive attitudes and support are crucial in the classroom. Students need to be encouraged to think of science as a way of opening many doors and making a contribution to the world around them.

According to Cary Sneider, a leading science educator and one of the writers of the Next Generation Science Standards, understanding engineering is essential for all citizens, workers, and consumers in a modern democracy. If the U.S. is to continue to play a significant role in the world economy, it is imperative that students be exposed to engineering design and problem solving thought processes. He goes on to say that the capability to formulate and solve problems is a valuable life skill. By including Engineering Design in the Oregon State Standards, students will have access to a wider range of viable careers because they will be prepared to take the appropriate courses in high school. Exposure to engineering design is also an important equity tool for girls and minority students.

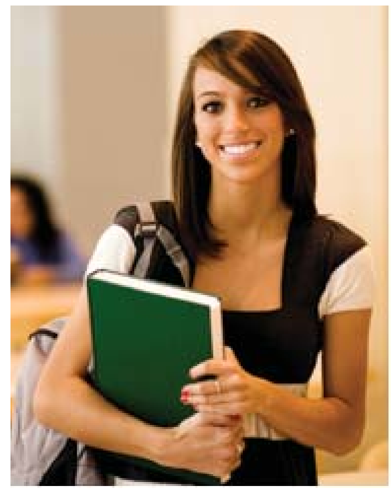
Acquiring Essential Skills While Learning Science

Engineering is ideal for integrating math and science. Using the Engineering Design process is an opportunity to provide a hands-on lesson that allows students to confront their preconceptions about scientific phenomena and how it relates to important learning goals. Lessons that engage students in Engineering Design can be effective whether they are structured or very “open,” with students pursuing answers to their own questions. According to *Effective Science Instruction: What Does Research Tell Us?* (Bainilower, et al, 2010) , “Whatever the mode of instruction, the research suggests that students are most likely to learn if teachers encourage them to think about ideas aligned to concrete learning goals and relate those ideas to real-life phenomena.”

One of the reasons that students’ understanding of science is increased is because of the immersion that hands-on learning offers. Engineering design can provide the **hook to motivate students**, addressing something they have wondered or wanted to know about. Learning science can then be enhanced by building on that knowledge and encouraging students to relate their design to real-world problems and applications (Bainilower, et al, 2010).

Why use the Engineering Design Process?

As part of the requirements for graduating high school in 2014, an additional element of Oregon's Essential Skills will be required: Apply mathematics in a variety of settings. Engineering design in the context of learning science is one such setting. Engineers use mathematics to analyze problems and develop solutions as well as test and analyze these solutions. The Engineering Design process can serve as a bridge between math and science and offers students a real-world way of thinking through and solving problems. Students benefit by acquiring a deeper understanding of science content at the same time they develop one of the essential skills needed to graduate.



The Engineering Design process will help students develop the skill to solve practical problems and also help develop the ability to read and comprehend a variety of texts, another essential skill required for graduation. Activity instructions are typically written in language that is somewhat technical, challenging students to lift their comprehension skills to a higher level. Students learn methods used by engineers to design and document their work. This allows them to read and comprehend a variety of text, write clearly and accurately and communicate their design – all skills that are part of Oregon's graduation requirements because they are important life skills.

Models and Simulations

Models are a way of describing a design and simulations are a way of testing designs. Modeling gives students the opportunity to build real things and in the process, use the Engineering Design process to learn science. Using models can change science lessons from passive to active. Models can enhance a student's understanding of how the world operates and open the door to alternative ways of thinking and problem solving.

Models can be small or big, simple or fancy. They can be physical, mathematical, and on the computer (software-based).

Models are a discovery tool to help:

- students understand the relationships between parts
- students visualize the interaction of moving or unmoving parts
- explore the consequences of these relationships
- explore new ways to think about the "need" that underlies the problem being solved
- develop spatial problem solving
- jump from a sketch on paper to three dimensions.

Why use the Engineering Design Process?

Models vs. Simulations		
	Model	**Simulation**
Scientific Inquiry Example	The way we think about the planets as a solar system including how gravity underlies the orbits of the planets.	A mechanical simulation that moves the planets around the sun based on the turning of gears or an animated graphical representation on a computer display showing the planets orbiting around the sun is a simulation.
Engineering Design Example	The way we estimate the load carrying capacity of a bridge based on how its elements are put together and the strengths of these elements is a model.	A balsa-wood bridge that allows us to test the load capacity of a design. Or an animated graphical computerized display of a bridge under load.

In K12 settings students often build physical simulations, usually referred to as scale models. A physical simulation is often a representation of a real-life object or phenomenon but on a different scale. Examples include a scale model of an atom, partly because a real atom is too small to see with an optical microscope or a balsa-wood bridge that fits on the top of a table, instead of across a river, that allows students to touch, analyze, and observe how it is used and what problem it solves. In a nutshell, physical simulations are realistic representations of ideas and possible solutions. They can be used to detect problems with a conceptual model and designs as well as make improvements to them.

In addition to physical simulations, computer simulations are used by scientists and engineers to better understand their models and designs. Computer simulations give students the opportunity to try different scenarios, identify flaws, test possible new solutions and see the strengths and weaknesses of their designs. Simulations also give designers a way to test their ideas and thereby save money on the materials required for a physical model. Computer simulations are beneficial when physical simulations are too large, small, or complex; the models take too long to build or are expensive to create; or the process being modeled is on a geologic, evolutionary or other time scale. One issue with computer simulation in the context of K12 science is that creating a computer simulation usually requires a good deal of programming expertise to create. Fortunately there are some excellent simulations available on the Internet, including some that use programming languages so simple that some students will be able to explore making changes and improvements to the simulations.

Connecting to Real-World Careers

The Engineering Design process teaches students how to think through a problem and use what they know and their creativity as well as materials and technology to make a better world. Using engineering design to learn science can also provide students additional insights into Science, Technology, Engineering and Math (STEM) careers. Because engineering is the application of science, technology, and math, students will be prepared to better understand a wide variety of STEM careers and make more informed choices on high school courses, college plans and an eventual career.

Being successful in any career requires much more than academic knowledge. Projects are done in teams, and products and services must compete in a global economy. The "soft" skills that students develop such as creativity, communication and leadership skills will serve them well in their future employment and life in general. The Engineering Design process, used to learn science content, can provide the tools to merge problem solving, communication, teamwork, leaderships, innovation, creativity, and critical thinking with learning science. Students who can apply concepts and integrate knowledge across academic disciplines and in practical settings will find it easier to find good jobs and succeed in life.

Engineering Design Process Description

Engineering Design Process Overview

Professional engineers use a variety of processes to solve problems. In the context of teaching and learning science we can simplify these processes into a step-by-step problem solving template. In the Oregon Science Standards this process is called Engineering Design and this process is a sister to the Science Inquiry process for teaching science. Just as the Science Inquiry process involves articulating a question and investigating possible answers to the question (leading to a better understanding of natural phenomena), the Engineering Design process involves articulating a problem and investigating possible solutions to the problem (leading to a better solution to the problem). In other words, engineering design is a way to put science to work to solve problems.

The Engineering Design process, at the middle school level, is a process of formulating problem statements, identifying criteria and constraints, proposing and testing possible solutions, incorporating modifications based on test data, and communicating the recommendations. The process is simplified for elementary grades and is a bit more complex at the high school level but still relies on the premise that engineering design exists to design and build things. Human needs, identifying criteria and constraints, proposing and testing solutions, and reworking the design to make it better are incorporated as students advance.

Characteristics of Engineering Design Processes and How They are Used

The Engineering Design process is not a rigid set of rules for solving every problem but more of a tool to focus and direct the process of problem solving and ways of thinking. Each problem is different and the solution may or may not go through each step in the process. For example, a student may discover in the process of researching a problem that there is already a solution available. The solution to the problem may involve using or adapting an existing solution.

In the Oregon Standards, the first step in the Engineering Design process is to define a problem associated with a need. In practice, this first step includes learning as much as possible about the problem or opportunity.

Engineering Design Process Description

Teaching Students About the Engineering Design Process

1. **Encourage teamwork** – Since students and engineers design in teams, this is a critical component. In "Generation Y - The Millennial Generation" in Generational Learning Styles, Julie Coates states that Generation Y's preferred learning environment combines teamwork and technology. She goes on to say that this generation is made up of confident, optimistic young people that feel valued and wanted. They are the most diverse generation in history, both ethnically and socially.
2. **Develop or encourage projects that are about people and making life better** Projects that include clean water, green energy, and/or low-carbon transportation alternatives can help students think globally and about future technologies.
3. **Start out by separating the boys and girls** – when first beginning projects that include engineering design, you may overcome culturally differentiated experiences by separating the boys and girls. In the early stages of developing spatial analysis skills and learning to build, girls may do much better if you start them out in an all-girl environment. After the girls and boys have been successful and built some self-confidence, having both genders on each team will help both genders. An even mix is best, even for professionals.
4. **Celebrate science and engineering** – Focus on current events in which engineers or scientists save lives, help the environment or serve their communities.
5. **Reverse engineer a favorite gadget** – Have students take apart devices such as cell phones, ipods or vacuum cleaners to see how they were designed and if they can imagine themselves as the designer, what could they do to make the design better? Whatever students are interested in – medicine, robotics, architecture, music or sports – there's probably a gadget needed to do it.
6. **Make math real-world** – Perceptions about math have changed the course of millions of lives. Tell students that math is just one tool in the engineering design box. Math and science are important tools to understanding the world but they are not the only problem-solving tools available. Without at least three years of high school math, students will be excluded from a wide variety of jobs including: Engineer, Programmer, Accountant, Biologist, Medical Technician, Architect and Doctor. Math is very important for intellectual development including creativity, constructive processes and problem-solving (Singh, Man pal, 2005). Other tools in the box include passion, communication skills, teamwork skills, common sense, analytical ability, persistence, writing skills, presentation skills and time management.
7. **Use graphics to represent ideas** – Graphics are a form of communication often overlooked. Communication, especially in engineering design, can mean the difference between getting the job done or not. In this age of instant and text messaging,

students need to take every opportunity to enhance their communication skills. All forms of communication are valuable and when using graphics or art to convey ideas, you may see the spark in a student's eye that wasn't there before. Tools such as Google Sketchup can effectively create this bridge.

Scientific Inquiry vs. the Engineering Design Process

Theodore von Karman once said:

"Scientists study the world as it is, engineers create the world that never has been."

Both engineering and science involve obtaining knowledge and using a set of practices.

According to *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* by The National Research Council, "the major goal of engineering is to solve problems that arise from a specific human need or desire. To do this, engineers rely on their knowledge of science and mathematics as well as their understanding of the engineering design process." Specifying what is needed and designing a solution for it provides students with an opportunity to practice the application of their understanding of science. The design process is also an important way for K-12 students to develop an understanding of engineering as a discipline and as a possible career path. The work of engineers, like the work of scientists, involves both individual and cooperative effort.

Engineering and science are similar in that both involve creative processes, and neither uses just one method.

Scientific Inquiry	Engineering Design
• The goal of science is to develop a set of coherent and mutually consistent theoretical descriptions of the world that can provide explanations over a wide range of phenomena. • Not necessarily driven by immediate practical needs. Could be driven by curiosity or with the aim of answering a question about the world or understanding an observed pattern. • For science, developing such explanations about the world constitutes success in and of itself, regardless of whether it has an immediate practical application.	• The goal of engineering is to evaluate prospective designs and then produce the most effective design for meeting the specifications and constraints. • Driven by practical human needs. • For engineering, success is measured by the extent to which a human need or want has been addressed.

Application to Science in High School

Correlation of Essential Skills and the Engineering Design Process

1. Read and comprehend a variety of text* *text includes but is not limited to all forms of written material, communications, media, and other representations in words, numbers, and graphics and visual displays using traditional and technological formats	
Reading Skill	**Steps of the Engineering Design Process**
1. Demonstrate the ability to read and understand text.	1. Define a problem that addresses a need. 3. Describe relevant scientific principles and knowledge.
2. Summarize and critically analyze key points of text, events, issues, phenomena or problems, distinguishing factual from non-factual and literal from inferential elements.	1. Define a problem that addresses a need. 2. Identify criteria, constraints and priorities. 3. Describe relevant scientific principles and knowledge.
3. Interpret significant ideas and themes, including those conveyed through figurative language and use of symbols.	1. Define a problem that addresses a need. 2. Identify criteria, constraints and priorities.
4. Follow instructions from informational or technical text to perform a task, answer questions, and solve problems.	5. Design and construct a proposed solution. 6. Test a proposed solution and collect relevant data.

Inventions that address human needs and aspirations are everywhere! Some of the most amazing include:

- Calculators
- Shoes
- Clothes
- Indoor Plumbing
- Tools for every job
- Antibiotics
- MP3 Players such as iPods
- Video Games
- Kitchen Appliances
- Robots
- Cell Phones and
- ATM Machines

2. Write Clearly and Accurately	
Writing Skill	**Steps of the Engineering Design Process**
1. Adapt writing to different audiences, purposes, and contexts in a variety of formats and media, using appropriate technology.	1. Define a problem that addresses a need. 2. Identify criteria, constraints and priorities. 3. Describe relevant scientific principles and knowledge.
2. Develop organized, well-reasoned, supported, and focused communications.	1. Define a problem that addresses a need. 2. Identify criteria, constraints and priorities. 3. Describe relevant scientific principles and knowledge.
3. Write to explain, summarize, inform, and persuade, including business, professional, technical, and personal communications.	5. Design and construct a proposed solution. 7. Evaluate the proposed solution in terms of design and performance criteria, constraints, priorities and trade-offs. 8. Identify possible design improvements.
4. Use appropriate conventions to write clearly and coherently, including correct use of grammar, punctuation, capitalization, spelling, sentence construction, and formatting.	4. Investigate possible solutions. 5. Design and construct a proposed solution. 8. Identify possible design improvements.

As a result of the space program, NASA's engineers are responsible for inventions such as:

- the hand held vacuum cleaner
- the firefighter breathing apparatus
- safer runways
- storm warning systems
- better sunglasses
- car crash technology
- freeze dried meals
- baby food
- improved air quality
- artificial limbs and much, much more.

Application to Science in High School

3. Apply Mathematics in a Variety of Settings	
Mathematics Skill	**Steps of the Engineering Design Process**
1. Interpret a situation and apply workable mathematical concepts and strategies, using appropriate technologies where applicable.	3. Describe relevant scientific principles and knowledge. 4. Investigate possible solutions. 5. Design and construct a proposed solution. 6. Test a proposed solution and collect relevant data.
2. Produce evidence, such as graphs, data, or mathematical models, to obtain and verify a solution.	6. Test a proposed solution and collect relevant data. 7. Evaluate the proposed solution in terms of design and performance criteria, constraints, priorities and trade-offs. 8. Identify possible design improvements.
3. Communicate and defend the verified process and solution, using pictures, symbols, models, narrative or other methods.	7. Evaluate the proposed solution in terms of design and performance criteria, constraints, priorities and trade-offs. 8. Identify possible design improvements.

Creating a new technology requires considering societal goals, costs, priorities, and trade-offs. Everything in life is a compromise.

Engineering Design Process for High School

1. Define a problem that addresses a need. Engineering begins with a problem that needs to be solved. Sometimes the problem is stated as a question, such as "How can we make sure people are safe in an earthquake? or "How can candy bars become healthier?" Other times, a problem is described as a scenario, for example "People using wheel chairs have said they have had trouble finding an entrance to a public building that they can use. Review the description of the building and design an improvement that will address their concerns." At this stage, you should encourage your students to ask questions to clarify the problem. The problem should be described in terms of solving a human need or other important need.

   To encourage your students to ask questions to better understand the nature of the problem, consider the following scenario: Mr. Avagadro, the 9th grade Science Teacher, likes to conduct science demonstrations for students and also enjoys seeing the students complete hands-on projects but often can't find his demonstration and project materials. He needs to organize the large inventory of supplies - some supplies are used every month but other supplies are only used once a year. Some supplies are chemicals that need to be insulated from the cold at night when the school's heat is off. He needs to know what supplies are available and what needs to be purchased. Tell the students that they should design a solution that would help him and their first step should be to ask questions until they completely understand the problem and can describe it in a clear paragraph starting with "The problem is that ...". Questions help students learn all aspects of the problem, helping break down the problem and its solution into smaller parts.

2. Identify criteria, constraints and priorities. Students should list and describe the criteria, constraints and priorities associated with solving the problem. The best criteria and constraints are usually quantitative. For instance, "supports at least 200 grams" is a clearly criterion than "supports a weight." In some cases you may provide some or all of the criteria, constraints and priorities and the students' job should paraphrase what you have provided in this section. In others cases you may ask them to come up with criteria, constraints and priorities based on their experience with the category of problem you have assigned. They may also want to survey possible users of the solution to better understand their needs or do library or web research on the need.

In the case of the organizational system for Mr. Avagadro, students may come up with criteria, constraints and priorities such as:

- Criteria: need to organize 6 demonstrations and the materials for 4 projects.
- Constraints: Must be low cost, easy to use and easily and quickly accessible.
- Priority: Must be easy to use and quickly accessible.

3. Describe relevant scientific principles and knowledge. Connecting relevant scientific principles and knowledge to the engineering design process ensures that projects will have broad importance across multiple science and engineering disciplines as well as providing a tool for understanding more complex ideas and solving problems.

In the case of Mr. Avagadro storing chemicals so that they don't get too cold at night when the school's heat is off, students may describe:

- Ways to measure the physical and chemical properties of a system.
- Ways to use the data obtained from scientific inquiry.
- How energy is transferred, transformed and conserved.

4. Investigate possible solutions and use concept of trade-offs to compare solutions in terms of criteria and constraints. High school students should understand that engineering problems

typically have many possible solutions. Students can start by coming up with several ideas even if some of them don't seem to address all the criteria, constraints and priorities. The possible solutions can be compared to the criteria, constraints and priorities as well as each other. Students should discuss the trade-offs between the possible solutions. Some students will think of additional solutions after they have analyzed and compared the initial solutions.

In the case of Mr. Avagadro, possible solutions may be:

- Separating demonstrations into clear labeled boxes all stacked in the same area.
- Putting each part for each project in a separate box.
- Creating an inventory list either manually or on a computer.
- Creating a list that tells where everything is located.

5. Design and construct at least one proposed solution. Students should choose at least one solution and build a prototype or model of the solution. Class discussions should include extra time to fully understand the problem and how the solution will solve the problem. Diagrams and a parts list for the model are suggested at this stage. If time and materials permit, the student should then build a model of the proposed solution or something like it.

6. Test a proposed solution(s), collect and process relevant data and incorporate modifications based on data from testing or other analysis. Students should test the solution they have built including making and recording measurements. The tests should determine whether the solution accomplishes the purposes described in the problem in terms of the criteria and constraints. The most important measurements are those that that relate to these criteria and constraints. If it is not possible to build the proposed solution or something similar to it, students should find another way of analyzing their solution. Students should consider how the testing has given them insights on improving the solution(s) and propose improvement to them.

In the case of Mr. Avagadro, students can record measurements such as:

- Time how long it takes to collect all of the parts needed for a demonstration or class project.
- Associated costs for producing the organization system.

7. Analyze data, identify uncertainties, and display data so that the implications for the solution being tested are clear. Using the test and measurements in the previous section, students should describe what they have learned about their solution. In particular they should discuss how well the solution met the criteria and stayed within the constraints. Because testing is never complete, students should identify and discuss what uncertainties remain

about their proposed solution(s). They should also discuss the trade-offs they made between the various criteria in the final solution(s).

8. Recommend a proposed solution, identify its strengths and weaknesses and describe how it is better than alternative designs as well as identifying further engineering that might be done to refine the recommendation. Students should recommend a particular solution as being best. Their recommendation should be based on the original criteria, constraints and priorities as well as their analysis. They should describe strengths and weaknesses of the recommended solution as well as how and why it is better overall than the other solutions that were considered. They should also describe how further engineering might be done to refine the recommendation.

What the Students Should Learn About the Process

The most basic level of the engineering design process, a level that all students should be comfortable doing, is to define a problem that addresses a human need. They should all understand criteria, constraints and priorities involved and connect the concepts to relevant scientific principles and knowledge. Each student will develop possible solutions and then build models and incorporate simulations of their models to evaluate, analyze and evaluate their solutions based on the criteria, constraints and priorities of the problem. Finally, high school students should be able to recommend a "best" solution based on their findings and data collection.

Students use the Engineering Design process to enhance the learning of science when they define problems and design solutions. Engineering design isn't a stand-alone component of the Oregon science standard. It should be used as a way to motivate, deepen students' interest in science content and also practice math and communication skills.

How the process can be used to enhance learning science as a sister to the Science Inquiry process

K. Eric Drexler, Ph.D., author of *Radical Abundance* said, "I think it's best to look beyond the mixture of inquiry and design in a project, and to consider instead its purpose. If the intended result is knowledge — a better model of what exists in the world and how it works — I think of it as science. If the intended result is a new product, process, or design methodology, I think of it as engineering."

Application to Science in High School

The focus of science is inquiry, and the focus of engineering is design.

	Role of inquiry	Role of design
In science:	increase knowledge	support inquiry
In engineering:	support design	increase function

Students use the Engineering Design process to enhance the learning of science when they define problems and design solutions. Engineering design isn't a stand-alone component of the Oregon science standard. It should be used as a way to motivate, deepen students' interest in science content and also practice math and communication skills.

On the OPAS website, there are two activities that have been compiled to assist using the Engineering Design Process to teach Physical Science and Earth and Space Science in middle school. Each activity provides an intriguing scenario, teaching guide, student handouts, and vocabulary alerts. The activities are each aligned to the Engineering Design portion of the Oregon State Standards to facilitate easy adoption into the classroom.

Connecting the Engineering Design Process

Connecting Engineering Design to Learning Life Science
Algae Machine Design Activity

In this engineering design lesson students will address problems associated with algae growth.

The lesson is divided into three parts.

1. Part one is a reading activity to help familiarize students to the algae growth process as well as its potential use as a biofuel.
2. Part two presents students with a prototype of an algae machine and asks students to improve upon its design by identifying weakness and generating solutions that address those problem areas.
3. In part three, students will build a prototype of their new design and evaluate its effectiveness by analyzing the algae growth rate

Tying it all together

Following is a table of how the ***Algae Machine*** lesson relates to the Engineering Design Process, the Oregon Engineering Design Standards, and the Life Science Standards. The steps exemplify how scientific inquiry and the engineering design process overlap to create meaningful lessons for students. This table is only a general guide – you may find more correlations and connections as you move through the lesson.

Steps of the EDP	**Engineering Design Standard Correlations**	**Life Science Standard Correlations**	**Algae Machine Correlations** *See the "Algae Machine Design" worksheet*
1. Define a problem that addresses a need	H.4D.1 Define a problem.	H.1L.4 Explain how cellular processes and cellular differentiation are regulated both internally and externally in response to the environments in which they exist.	Students will identify problems in the design of a prototype algae machine.
2. Identify criteria, constraints and priorities	H.4D.1 Specify criteria for a solution within specific constraints or limits based on science principles.	H.1L.4 Explain how cellular processes and cellular differentiation are regulated both internally and externally in response to the environments in which they exist. H.2L.1 Explain how energy and chemical elements pass through systems. Describe how chemical elements are combined and recombined in different ways as they cycle through the various levels of organization in biological systems.	Students will identify the criteria, constraints and trade-offs.

Connecting the Engineering Design Process

Steps of the EDP	Engineering Design Standard Correlations	Life Science Standard Correlations	Algae Machine Correlations *See the "Algae Machine Design" worksheet*
3. Describe relevant scientific principles and knowledge	H.4D.1 Define a problem and specify criteria for a solution within specific constraints or limits based on science principles.	H.1L.4 Explain how cellular processes and cellular differentiation are regulated in response to the environment. H.2L.1 Explain how energy and chemical elements pass through systems. Describe how chemical elements are combined and recombined in different ways as they cycle through the various levels of organization in biological systems. H.2L.2 Explain how ecosystems change in response to disturbances and interactions.	Students will identify problems in the design of a prototype algae machine and brainstorm solutions.
4. Investigate possible solutions and use the concept of trade-offs to compare solutions in terms of criteria and constraints.	H.4D.1 Generate several possible solutions to a problem and use the concept of trade-offs to compare them in terms of criteria and constraints.	H.2L.1 Explain how energy and chemical elements pass through systems. Describe how chemical elements are combined and recombined in different ways as they cycle through the various levels of organization in biological systems. H.2L.2 Explain how ecosystems change in response to disturbances and interactions. Analyze the relationships among biotic and abiotic factors in ecosystems.	• Students will brainstorm solutions. • Students will evaluate their design ideas using the concepts of trade-offs, criteria, and constraints. • Students will analyze pre-generated data on an algae machine prototype. They will use their analysis of this data to incorporate modifications in their own designs.
5. Design and construct at least one proposed solutionn	H.4D.2 Create and test or otherwise analyze at least one of the more promising solutions.	H.2L.1 Explain how energy and chemical elements pass through systems. Describe how chemical elements are combined and recombined in different ways as they cycle through the various levels of organization in biological systems. H.2L.2 Explain how ecosystems change in response to disturbances and interactions. Analyze the relationships among biotic and abiotic factors in ecosystems.	• Students will evaluate their design ideas. • Students will build a small-scale algae machines.
6. Test a proposed solution(s), collect and process relevant data and incorporate modifications based on data from testing or other analysis	H.4D.2 Create and test or otherwise analyze at least one of the more promising solutions. Collect and process relevant data. Incorporate modifications based on data from testing or other analysis.	H.2L.1 Explain how energy and chemical elements pass through systems. Describe how chemical elements are combined and recombined in different ways as they cycle through the various levels of organization in biological systems. H.2L.2 Explain how ecosystems change in response to disturbances and interactions. Analyze the relationships among biotic and abiotic factors in ecosystems.	• Students will build a small-scale algae machines and collect data on its effectiveness by determining algae growth rate. • Students will analyze pre-generated data on an algae machine prototype. They will use their analysis of this data to incorporate modifications in their own designs.

Connecting the Engineering Design Process

Steps of the EDP	Engineering Design Standard Correlations	Life Science Standard Correlations	Algae Machine Correlations *See the "Algae Machine Design" worksheet*
7. Analyze data, identify uncertainties, and display data so that the implications for the solution being tested are clear	H.4D.3 Analyze data, identify uncertainties, and display data so that the implications for the solution being tested are clear.	H.2L.1 Explain how energy and chemical elements pass through systems. Describe how chemical elements are combined and recombined in different ways as they cycle through the various levels of organization in biological systems. H.2L.2 Explain how ecosystems change in response to disturbances and interactions. Analyze the relationships among biotic and abiotic factors in ecosystems. H.2E.4 Evaluate the impact of human activities on environmental quality and the sustainability of Earth systems. Describe how environmental factors influence resource management.	• Students will analyze pre-generated data on an algae machine prototype. They will use their analysis of this data to incorporate modifications in their own designs. • Students will present their data in an easy-to-read graph format and write an analysis that clearly communicates both the uncertainties in the data as well as the implications for their prototype.
8. Recommend a proposed solution, identify its strengths and weaknesses and describe how it is better than alternative designs as well as identifying further engineering that might be done to refine the recommendation.	H.4D.4 Recommend a proposed solution, identify its strengths and weaknesses, and describe how it is better than alternative designs. Identify further engineering that might be done to refine the recommendations.	H.1L.4 Explain how cellular processes and cellular differentiation are regulated both internally and externally in response to the environments in which they exist. H.2L.1 Explain how energy and chemical elements pass through systems. Describe how chemical elements are combined and recombined in different ways as they cycle through the various levels of organization in biological systems. H.2L.2 Explain how ecosystems change in response to disturbances and interactions. Analyze the relationships among biotic and abiotic factors in ecosystems.	After building and evaluating their first solutions, students will write a paragraph detailing its strengths, a paragraph describing its weaknesses, and either a paragraph or a new sketch of recommended modifications.

Connecting the Engineering Design Process

Connecting Engineering Design to Learning Physical Science

Littlefoot's Lil' Coaster Ride Design Activity

In this engineering design lesson students will address the problems associated with creating carts for a kiddie roller coaster. The second part of the lesson presents students with a scenario: Bigfoot's Adventure Fun Time Land, a new amusement park on Mount Hood, wants to convert old railroad tracks into a kiddie coaster ride but they need help designing the carts.

The lesson is divided into two parts.

1. Part one is a background reading activity that familiarizes students with the physics behind roller coasters.
2. The second part of the lesson presents students with a scenario: Bigfoot's Adventure Fun Time Land, a new amusement park on Mount Hood, wants to convert old railroad tracks into a kiddie coaster ride but they need help designing the carts.

Tying it all together

Following is a table of how the ***Littlefoot's Lil' Coaster Ride*** lesson relates to the Engineering Design process, the Oregon Engineering Design Standards, and the Physical Science Standards. The steps exemplify how scientific inquiry and the engineering design process overlap to create meaningful lessons for students. This table is only a general guide – you may find more correlations and connections as you move through the lesson.

Steps of the EDP	**Engineering Design Standard Correlation**	**Physical Science Standard Correlation**	**Coaster Ride Correlations** *See the LIttlefoot's Lil' Coaster Student Handout*
1. Define a problem that addresses a need	H.4D.1 Define a problem and specify criteria for a solution within specific constraints or limits based on science principles.	H.2P.3 Describe the interactions of energy and matter including the law of conservation of energy.	Students will identify problems in the design of a cart for a kiddie coaster ride and brainstorm solutions.
2. Identify criteria, constraints and priorities	H.4D.1 Define a problem and specify criteria for a solution within specific constraints or limits based on science principles.	H.2P.3 Describe the interactions of energy and matter including the law of conservation of energy.	• Students will identify problems in the design of a cart for a kiddie coaster ride and brainstorm solutions. • Students will evaluate their design ideas using the concepts of trade-offs, criteria, and constraints.
3. Describe relevant scientific principles and knowledge	H.4D.1 Define a problem and specify criteria for a solution within specific constraints or limits based on science principles.	H.2P.2 Explain how physical and chemical changes demonstrate the law of conservation of mass. H.2P.3 Describe the interactions of energy and matter including the law of conservation of energy.	Students will identify problems in the design of a prototype coaster ride and brainstorm solutions.

Connecting the Engineering Design Process

Steps of the EDP	**Engineering Design Standard Correlation**	**Physical Science Standard Correlation**	**Coaster Ride Correlations** *See the LIttlefoot's Lil' Coaster Student Handout*
4. Investigate possible solutions and use concept of trade-offs to compare solutions in terms of criteria and constraints.	H.4D.1 Generate several possible solutions to a problem and use the concept of trade-offs to compare them in terms of criteria and constraints.	H.2P.3 Describe the interactions of energy and matter including the law of conservation of energy. H.2P.4 Apply the laws of motion and gravitation to describe the interaction of forces acting on an object and the resultant motion.	• Students will evaluate their design ideas using the concepts of trade-offs, criteria, and constraints. • Students will analyze data to incorporate modifications in their own designs.
5. Design and construct at least one proposed solution	H.4D.2 Create and test or otherwise analyze at least one of the more promising solutions.	H.2P.4 Apply the laws of motion and gravitation to describe the interaction of forces acting on an object and the resultant motion.	• Students will build a coaster cart.
6. Test a proposed solution(s), collect and process relevant data and incorporate modifications based on data from testing or other analysis	H.4D.2 Create and test or otherwise analyze at least one of the more promising solutions. Collect and process relevant data. Incorporate modifications based on data from testing or other analysis.	H.2P.3 Describe the interactions of energy and matter including the law of conservation of energy. H.2P.4 Apply the laws of motion and gravitation to describe the interaction of forces acting on an object and the resultant motion.	• Students will build a coaster cart and collect data. • Students will analyze data to incorporate modifications in their own designs.
7. Analyze data, identify uncertainties, and display data so that the implications for the solution being tested are clear	H.4D.3 Analyze data, identify uncertainties, and display data so that the implications for the solution being tested are clear.	H.2P.2 Explain how physical and chemical changes demonstrate the law of conservation of mass. H.2P.3 Describe the interactions of energy and matter including the law of conservation of energy. H.2P.4 Apply the laws of motion and gravitation to describe the interaction of forces acting on an object and the resultant motion.	• Students will analyze data to incorporate modifications in their own designs. • Students will present their data in an easy-to-read graph format, and write an analysis that clearly communicates both the uncertainties in the data as well as the implications for their prototype.
8. Recommend a proposed solution, identify its strengths and weaknesses and describe how it is better than alternative designs as well as identifying further engineering that might be done to refine the recommendation.	H.4D.4 Recommend a proposed solution, identify its strengths and weaknesses, and describe how it is better than alternative designs. Identify further engineering that might be done to refine the recommendations.	H.2P.4 Apply the laws of motion and gravitation to describe the interaction of forces acting on an object and the resultant motion.	After building and evaluating their first solutions, students will write a paragraph detailing its strengths, a paragraph describing its weaknesses, and either a paragraph or a new sketch of recommended modifications.

Conclusion

What now, next steps

The next step is to participate in a training conducted by a facilitator who will provide activities that can be taken back to the classroom, as well as sample work samples, engineering design charts and references, templates and checklists. In late 2012 the Oregon University System offered school districts a competitive grant opportunity that provides winning school districts and schools small incentive grants to assist them in offering these workshops to their teachers. Similar grant opportunities may be offered in the future and some schools and school districts may decide to offer the workshops on their own. For information on this possibility, please contact XXXX@ous.edu. Teachers who attend a workshop will be given the opportunity to think about how they teach, draw upon the collective wisdom of their colleagues, participate in hands-on activities and walk away with Engineering Design Process lessons to be used in their school with their materials.

If you cannot attend a workshop or you want to get started immediately, the next steps are considering how to adapt what you have learned from this primer to existing and new science lessons. Get together with your colleagues to brainstorm. Use the Engineering Design process to develop a method for deploying engineering design in the classroom.

The Engineering Design Process	Possibilities
1. Define the problem or need	Adapting what you have learned from this primer
2. Identify the criteria, constraints and priorities	Criteria: using the engineering design process to teach science Constraints: materials, time, collaboration Priorities: Students use the process to learn science concepts
3. Describe relevant scientific principles and knowledge	Use what you know about science instruction to adapt the lessons
4. Investigate possible solutions and use concept of trade-offs to compare solutions in terms of criteria and constraints.	Research on the Internet to see what others are doing or collaborate with a colleague.
5. Design and construct at least one proposed solution	Modify the lesson.

Conclusion

The Engineering Design Process	Possibilities
6. Test a proposed solution(s), collect and process relevant data and incorporate modifications based on data from testing or other analysis	Give it a try and see if it works.
7. Analyze data, identify uncertainties, and display data so that the implications for the solution being tested are clear	Evaluate how it went.
8. Recommend a proposed solution, identify its strengths and weaknesses and describe how it is better than alternative designs as well as identifying further engineering that might be done to refine the recommendation.	Redesign the lesson to make it better.

Key Terms

Constraints — Limits on possible solutions. When we solve a practical problem we usually have limits on how big the solution can be, how much it can cost, how easy it is to use, etc.

Criteria — The things your solution should do or be (i.e. cheap to manufacture locally). Engineering problems are usually described in terms of a set of goals that become the criteria against which we judge possible solutions.

Design (noun) – A plan for a product, process, or system created to solve a problem.

Design (verb) — The process of modifying or inventing a product, process, or system to solve a problem, including the look, feel, features and performance.

Innovation – A new or improved means to solve a problem.

Invention – The first occurrence of a new technology designed to solve a problem or meet a need. Invention is closely related to innovation. An invention often indicates an intent to market the product or to protect the intellectual property with a patent or other process.

Knowledge — When a practical problem is being solved, we need to consider which scientific facts about the problem and possible solutions to the problem might be needed to solve the problem. In many cases we need to gather more scientific information to come up with a good solution.

Model – In relation to using the engineering design process, a model is something that represents a design. It may function like the design or represent the size and shape of the designed object, or be a graphical representation (e.g. a scale drawing) of an object or a process.

Modifications – Changes to a design that are intended to improve performance. Making modifications to a design is a normal step in the design process since the first design is almost never perfect.

Need — The reason why we want to solve a problem. Most engineering problems relate to a need that relates to people, society or the world around us.

Optimization – The process of considering and making design tradeoffs in order to maximize performance with respect to a criterion or prioritized list of criteria.

Practical – The characteristic that a problem or solution has a real-world application.

Priorities – A ranking of criteria in their order of importance.

Priority — The relative importance of the criteria and constraints. Usually some criteria are more important than others. Likewise for constraints.

Principles — Most engineering design solutions use scientific principles to meet the goals of the project. One example would be various types of energy can be transformed into thermal energy or heat. Engineers know that energy cannot be created or destroyed so therefore, designing something that uses a light bulb to illuminate a space will also create some heat in the space.

Key Terms

Problem — Something that needs to be solved and usually the goal of an engineering design project. Most engineering projects relate to a practical problem that provides a benefit to people or improves upon an existing solution.

Prototype – A not yet final working model of a design that is usually constructed to test performance or other criteria.

Simulation — A representation of a model or solution, tested under various conditions or changes in input, that exhibits at least some of the aspects of the real situation or solution so that it can be studied and improved. Simulations can be physical representations or implemented on a computer.

Solution — In relation to using the engineering design process, a solution is a possible way of solving a practical problem.

Trade-off — Practical problems almost always have many solutions. When we compare one solution to another, doing a better job of achieving one criterion often means doing less well on another criterion. In other words, we are forced to trade-off one criterion for another.

Additional Resources

Methods and tools to produce work samples

- Oregon High School Engineering Design Scoring Guides and notebook templates
  Web reference: www.ode.state.or.us/search/page/?id=32 or tinyurl.com/l8prupx
- Oregon Science Inquiry and Engineering Design Work Sample Resources: tinyurl.com/SIEDWS
- Engineering Design Work Sample Justification Sheet for scoring student work
  Web reference: tinyurl.com/cqof2dy
- Secondary Sample Student Language Engineering Design Scoring Template. This document represents one good approach for assisting students in developing a work sample using engineering design. Many other approaches are also possible. This template has been successfully used by several teachers in Oregon to help students produce Engineering Design Work Samples.
  Web reference: tinyurl.com/ctkoxmz

Additional Resources

Web Resources

- High School sample activities: http://opas.ous.edu/EDOSC/Materials.php
- Request for application: http://www.oregonetic.org/grant-info
- Engineering Design Core and Content Standards for all bands available on: Pages 25 and 26 of http://bit.ly/V0nf7C
- Next Generation Science Standards : www.nextgenscience.org
- *Scientific and Engineering Practices in K-12 Classrooms: Understanding a Framework for K-12 Science Education* by Rodger W. Bybee: http://bit.ly/UDeO6G

Pre-Engineering Curriculum and Projects

- Project Lead the Way - Project Lead the Way (PLTW) is a non-profit organization that promotes engineering courses for middle (Gateway to Technology) and high school (Pathway to Engineering) students. www.pltw.org
- Materials World Modules - Materials World Modules focus on materials engineering – books, kits and training for middle and high school students. www.materialsworldmodules.org
- Teachengineering.org - Funded as part of the NSF-supported National Science Digital Library (NSDL) to provide educational resources for STEM (science, technology, engineering and mathematics) education. TeachEngineering.org is a searchable, web-based digital library collection populated with standards-based engineering curricula for use by K-12 teachers and engineering faculty. www.teachengineering.org
- Design Squad - Design Squad is a reality-based competition show aimed at kids and people of all ages. Its goal is to get viewers excited about engineering and the design process. The series has free engineering resources you can use in classrooms, after-school programs, and event settings to get middle school kids excited about engineering. www.designsquad.org